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Technical, Supply and Economic Assessments

February 1982

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U.S. Department of Energy
Assistant Secretary for Conservation and
Renewable Energy
Office of Vehicle and Engine R & D
Under Contract No. DE-AC01-80CS50179

Alternative Fuels Utilization Program

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I

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Prepared by:
Energy Conservation Directorate
The Aerospace Corporation
El Segundo, California 90245
Under Contract No. DE-AC01-80CS50179

Prepared for:
U.S. Department of Energy
Assistant Secretary for Conservation and
Renewable Energy
Office of Vehicle and Engine R & D
Washington, DC 20585

Alternative Fuels Utilization Program

II

FOREWORD

This report, prepared by The Aerospace Corporation for the Office of Vehicle and Engine R&D of the Department of Energy, provides an assessment of issues related to the supply and use of methane-related fuels in automotive spark-ignition and diesel engines. The term methane, as used in this report, includes and is interchangeable with natural gas as well as synthetic (or substitute) natural gas derived from coal, biomass, waste products or other renewable resources, provided methane is the predominant constituent. Methanol was included in this study because it is a liquid fuel producible from either natural gas or the same resources as synthetic natural gas. The assessment is based primarily on a comprehensive review of the open literature, supplemented by discussions with manufacturers and users of automotive natural gas systems and related equipment.

The report is divided into three volumes. This volume, Volume II, Technical, Supply, and Economic Assessments, provides documentation of all study efforts and results. The areas addressed include vehicle fuel system and fueling station technology; vehicle performance, fuel economy, and emissions; resource energy utilization efficiency; potential petroleum displacement by alternative-fueled fleets; fuel supply; vehicle safety; user economics; and research needs.

Volume I, Executive Summary, provides summaries of results for all technical, supply, and economic assessments, and identifies research needed for the expanded use of natural gas in the automotive sector.

Volume III, Appendices, provides data and evaluations in several technical areas which supplement Volume II assessments. Also included are the comments submitted by two organizations after their review of the draft report.

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ABSTRACT

This report assesses the use of methane-related fuels, derived from a variety of sources, in highway vehicles. The term methane, as used in this report, includes and is interchangeable with natural gas (NG) as well as synthetic (or substitute) natural gas (SNG), provided methane is the predominant constituent. Methanol is included in this study because it can be produced from NG or the same resources as SNG, and because it is a liquid fuel at normal ambient conditions. Technological, operational, efficiency, petroleum displacement, supply, safety, and economic issues are analyzed. The assessment is intended to satisfy Section 7(a) of the Methane Transportation Research, Development, and Demonstration Act of 1980 (PL 96-512), which focuses on expanded methane use in automotive fleet vehicles and farm equipment. Evaluations of institutional barriers and other alternative fuels were not included in this contract.

About 275,000 Italian and 20,000 domestic vehicles presently use NG. Conversion kits are commercially available for spark-ignition engines, but not for diesel vehicles. A typical dual-fuel (NG or gasoline) light-duty vehicle conversion costs $1250 to $2050, adds 175 to 300 pounds to vehicle weight, and adds to the gasoline driving range a range of 60 to 120 miles on compressed natural gas (CNG), or 200 to 400 miles on cryogenic liquefied natural gas (LNG). Both CNG and LNG require special fueling facilities and vehicle tanks. Methanol conversions are commercially available for $1500 to $2200. They do not significantly affect vehicle weight, but diminish driving range by 35 to 50 percent unless tank size is increased. For the most part, methanol fueling facilities and fuel systems are similar to those for gasoline, except for the use of different materials.

In principle, both NG and methanol allow more efficient engine operation than gasoline. In practice, engines are at present rarely optimized for NG and methanol. On the basis of energy expended from resource extraction to end use, only optimized LNG vehicles are more

efficient than their gasoline counterparts. By 1985, up to 16 percent of total United States petroleum-based highway vehicle fuel could be displaced by large fleets with central NG fueling depots. Excluding diesel vehicles, which need technology advances to use NG, savings of 8 percent are projected. Methanol use by large fleets could displace up to 8 percent of petroleum-based highway vehicle fuel from spark-ignition vehicles and another 9 percent from diesel vehicles with technology advances.

United States NG supply appears adequate to accommodate fleet use. Supply projections, future price differential versus gasoline, and user economics are uncertain. In many cases, attractive paybacks can occur. CNG now costs on average about $0.65 less than gasoline, per energy-equivalent gallon. Methanol supply projections, future prices, and user economics are even more uncertain. Current and projected near-term methanol supplies are far from adequate to support fleet use. Methanol presently costs more than gasoline on an equal-energy basis, but is projected to cost less if produced from coal instead of NG or petroleum.

ACKNOWLEDGMENTS

Appreciation is acknowledged for the guidance and assistance provided by Dr. Ralph D. Fleming of the Department of Energy, Office of Vehicle and Engine R&D, who served as Project Manager for this study. Appreciation is also extended to many individuals and organizations who provided reference material and reviewed the draft of the report. In particular, the cooperation of Dual Fuel Systems, Inc., the Gas Service Energy Corporation, and the Environmental Protection Agency, who participated in the vehicle test program, is gratefully acknowledged.

During the course of this effort, industry involvement was solicited at all stages, from the study definition workshop in August 1980, through three bimonthly review meetings, and in two successive reviews of draft material. The cooperation of the following organizations in that process is gratefully acknowledged: American Gas Association; Argonne National Laboratory; Beech Aircraft Corporation; CNG Services, Inc.; Dual Fuel Systems, Inc.; Escher:Foster Technology Associates, Inc.; Ford Motor Company; Gas Service Energy Corporation; General Motors Corporation; Institute of Gas Technology; LNG Services, Inc.; Mueller Associates, Inc.; NCF Industries; New York State Energy Office; United States Environmental Protection Agency; and United States General Services Administration. Many constructive comments and suggestions were received from the reviewers, and these are incorporated in this report. In addition, appreciation is extended to the current users and developers of natural gas and methanol equipment who cooperated in providing data for this study.

The report is based on work performed by J. E. Clark, R. R. Covey, J. J. Donnelly, Jr., A. S. Levine, D. L. Levine, M. K. Martin, W. U. Roessler, and H. M. White.

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CONTENTS

FOREWORD..... iii

ABSTRACT..... v

ACKNOWLEDGMENTS..... vii

1. INTRODUCTION..... 1-1

2. FUEL SYSTEM TECHNOLOGY..... 2-1
   - 2.1 Vehicle Fuel Systems..... 2-2
   - 2.2 Component Technology..... 2-15
   - 2.3 System Weights, Volumes, and Costs..... 2-28
   - 2.4 Fueling Stations..... 2-31
   - 2.5 References..... 2-37

3. VEHICLE OPERATION..... 3-1
   - 3.1 Natural Gas Advantages and Disadvantages..... 3-1
   - 3.2 Natural Gas Vehicle Test Data..... 3-10
   - 3.3 Natural Gas Operational Experience..... 3-13
   - 3.4 Methanol..... 3-13
   - 3.5 References..... 3-18

4. RESOURCE ENERGY UTILIZATION..... 4-1
   - 4.1 Logistic Chain Efficiency..... 4-1
   - 4.2 Vehicle Energy Efficiency..... 4-5
   - 4.3 Overall Resource Energy Consumption..... 4-18
   - 4.4 References..... 4-22

5. POTENTIAL PETROLEUM DISPLACEMENT..... 5-1
   - 5.1 Passenger Car Fleets..... 5-1
   - 5.2 Truck and Bus Fleets..... 5-11
   - 5.3 Petroleum Fuel Consumption for Fleet Vehicles..... 5-22
   - 5.4 Petroleum Displacement Potential..... 5-22
   - 5.5 Market Penetration Considerations..... 5-28
   - 5.6 References..... 5-30

CONTENTS (Continued)

6. FUEL SUPPLY 6-1
6.1 Resources and Reserves 6-2
6.2 Production Technology 6-20
6.3 Supply Projections 6-23
6.4 Projected Fuel Prices 6-37
6.5 References 6-42

7. VEHICLE SAFETY 7-1
7.1 Methane Vehicle Safety Literature Review 7-2
7.2 Hazards Based on Fuel Properties 7-13
7.3 Fuel System Hazards in Normal Operation 7-22
7.4 Fuel System Hazards Under Accident Conditions 7-28
7.5 References 7-39

8. USER ECONOMICS 8-1
8.1 Factors Impacting NG User Economics 8-1
8.2 Results of Recent NG Economic Assessments 8-1
8.3 Algorithm for Analysis of NG Payback Period 8-3
8.4 CNG Fueling Station Cost Model 8-4
8.5 Before-Tax Payback Period for CNG 8-6
8.6 Summary of CNG User Economics 8-10
8.7 LNG User Economics 8-11
8.8 Methanol User Economics 8-12
8.9 References 8-13

9. RESEARCH NEEDS 9-1
9.1 Performance, Fuel Economy, and Emissions of Natural-Gas-Fueled Vehicles 9-1
9.2 Vehicle Safety 9-2
9.3 Studies and Assessments 9-3

GLOSSARY G-1

TABLES

2-1. Comparison of Gas Storage Methods..... 2-20

2-2. Physical Characteristics of ECMI Cryogenic Tanks..... 2-26

2-3. Weights of Typical Natural Gas Systems for Light-Duty Vehicles..... 2-28

2-4. Fuel and Storage Tank Parameters..... 2-29

2-5. CNG Compressor Characteristics..... 2-33

2-6. CNG Fueling Station Costs..... 2-34

2-7. LNG Fueling Station Costs..... 2-36

3-1. Advantages and Disadvantages of Natural Gas Compared with Gasoline..... 3-2

3-2. Thermochemical Properties of Fuels..... 3-3

3-3. Exhaust Hydrocarbon Reactivities with Gasoline and Natural Gas Fuels..... 3-8

3-4. Emissions and Power with Natural Gas Relative to Gasoline..... 3-9

3-5. Summary of Natural Gas Vehicle Data - Fleet Operators..... 3-11

3-6. Summary of Natural Gas Vehicle Data - Experimental Vehicles..... 3-11

3-7. Operational Experience with Natural-Gas-Fueled Vehicles..... 3-14

3-8. Advantages and Disadvantages of Methanol Compared with Gasoline..... 3-14

3-9. Summary of Selected Methanol Vehicle Data..... 3-18

4-1. Logistic Chain Efficiency from Resource to Vehicle Input -- Energy Resource: Natural Gas..... 4-2

4-2. Logistic Chain Efficiency from Resource to Vehicle Input -- Energy Resource: Coal..... 4-2

4-3. Logistic Chain Efficiency from Resource to Vehicle Input -- Energy Resource: Wood..... 4-3

TABLES (Continued)

4-4. Logistic Chain Efficiency from Resource to Vehicle Input -- Energy Resource: Municipal Solid Waste..... 4-3

4-5. Logistic Chain Efficiency from Resource to Vehicle Input -- Energy Resource: Petroleum..... 4-4

4-6. Logistic Chain Efficiency from Resource to Vehicle Input..... 4-6

4-7. Characteristics of Baseline Light- and Heavy-Duty Vehicles Used for Simulation Study..... 4-7

4-8. Relative Thermal Efficiency and Power of Retrofit Dual-Fuel and Single-Fuel Vehicles..... 4-8

4-9. Fuel System Parameters for Simulated Light-Duty Spark-Ignition Vehicles..... 4-10

4-10. Simulation Results for Light-Duty Spark-Ignition Alternative-Fuel Vehicles..... 4-12

4-11. Simulation Results for Light-Duty Diesel Alternative-Fuel Vehicles..... 4-15

4-12. Simulation Results for Heavy-Duty, Spark-Ignition Alternative-Fuel Vehicles..... 4-16

4-13. Simulation Results for Heavy-Duty Diesel Alternative-Fuel Vehicles..... 4-17

4-14. Summary of Relative Vehicle Energy Consumption..... 4-19

4-15. Overall Resource Consumption for Light-Duty SI-Engine Vehicles..... 4-19

4-16. Overall Resource Consumption for Light-Duty Diesel Vehicles..... 4-20

4-17. Overall Resource Consumption for Heavy-Duty SI-Engine Vehicles..... 4-20

4-18. Overall Resource Consumption for Heavy-Duty Diesel Vehicles..... 4-21

4-19. Summary of Relative Resource Energy Consumption: Petroleum Versus Natural Gas Resource Base..... 4-21

TABLES (Continued)

5-1. Historical Breakdown for U.S. Cars in Business Fleets of Ten or More Cars..... 5-2

5-2. Characteristics of Company Leased Passenger Cars..... 5-3

5-3. Composition of Leased Business Fleets in 1981..... 5-3

5-4. Composition of Company-Owned Business Fleets in 1981..... 5-4

5-5. Sales Weighted EPA Composite Fuel Economy, Domestic and Captive Import Cars..... 5-5

5-6. Selected Characteristics of Police Fleets..... 5-7

5-7. Statistical Summary for Cars in Fleets of Ten or More in 1981..... 5-10

5-8. Projected Car Petroleum Fuel Consumption..... 5-11

5-9. 1977 Truck Statistics..... 5-12

5-10. Definition of Truck Weight Categories..... 5-13

5-11. Distribution of Trucks in Fleets of Six or More in 1977..... 5-14

5-12. Approximate Truck Fuel Consumption in 1977..... 5-15

5-13. Projected Truck Population..... 5-16

5-14. Projected Truck Fleets of Six or More..... 5-17

5-15. Statistical Summary for Commercial Trucks in Fleets of Six or More in 1977..... 5-18

5-16. Truck Fleet Fuel Economy Projections..... 5-19

5-17. Projected Private and Commercial Truck Fleet Fuel Consumption..... 5-19

5-18. Statistical Summary for Government Truck Fleets - 1979..... 5-21

5-19. Statistical Summary for Bus Fleets in 1978..... 5-22

5-20. Projected Fleet Petroleum-Based Fuel Consumption..... 5-23

TABLES (Continued)

5-21. Potential Displacement of Petroleum-Based Fuels by Alternative-Fuel Systems..... 5-23

5-22. Potential Petroleum-Based Fuel Displacement for Trucks in Fleets of Six or More Based on 1977 Truck Data..... 5-25

5-23. Potential Petroleum-Based Fuel Displacement in 1985 by Natural Gas Fleet Cars and Private and Commercial Trucks..... 5-26

5-24. Operational Experience with Natural-Gas-Fueled Vehicles..... 5-31

6-1. Definition of Resource and Reserve Categories..... 6-3

6-2. Major World Gas Reserves as of 1 January 1981..... 6-4

6-3. Major Gas-Producing Countries..... 6-5

6-4. Supply of Proved Natural Gas Reserves at Current Production Rate..... 6-5

6-5. Potential Natural Gas Resource as of 1 January 1981..... 6-7

6-6. Estimated Coal-Bed Gas Resources..... 6-9

6-7. Estimated Recoverable Shale Gas Resources..... 6-11

6-8. Estimated Producible Shale Gas in the Appalachian Basin..... 6-11

6-9. Estimated Total and Recoverable Tight Gas Resources..... 6-13

6-10. Estimated Recoverable Tight Sands Resources..... 6-13

6-11. Identified United States Coal Resources..... 6-15

6-12. Projected Total and Available Municipal Solid Waste Generation..... 6-19

6-13. Efficiencies for CNG and LNG Production from Natural Gas, Coal, Wood, and MSW..... 6-24

6-14. Efficiencies for Methanol Production from Natural Gas, Coal, Wood, and MSW..... 6-25

6-15. Projection of U.S. Gas Supply from all Sources..... 6-27

TABLES (Continued)

6-16. Comparison of 1990 Forecasts of U.S. Gas Supply..... 6-33

6-17. Projected Methanol Demand and Supply in the United States and the World..... 6-37

6-18. U.S. Energy Prices: History and Projections..... 6-39

6-19. Projected Prices of Fuels Produced from Wood and MSW..... 6-41

7-1. Peak Acceleration during Dual-Fuel Vehicle Safety Impact Tests..... 7-3

7-2. CNG Cylinder Drop Test Conditions..... 7-4

7-3. Component Sled Test Summary..... 7-5

7-4. Dual-Fuel Vehicle Fleets Surveyed..... 7-9

7-5. Physical Properties of Fuels..... 7-14

7-6. Thermochemical Properties of Fuels..... 7-15

7-7. Fuel Health Hazards..... 7-18

7-8. Criteria for Fuel Hazards Comparison..... 7-20

7-9. Ranking of Relative Hazards Based on Fuel Properties..... 7-21

7-10. Comparison of Burning and Heat Release Rates of Spilled Liquid Pools Reported by Two Sources..... 7-22

7-11. Safety-Related Component Malfunctions..... 7-29

8-1. Summary of Recent CNG User Economic Studies..... 8-2

8-2. Description of Scenarios..... 8-8

8-3. Discounted Before-Tax Payback Period for Optimally Sized Fueling Stations..... 8-8

8-4. Sensitivity of Discounted Before-Tax Payback Period of Economic Parameter Variations for CNG Vehicle Fleets..... 8-10

FIGURES

2-1. Vehicular CNG System Schematic..... 2-5

2-2. Typical CNG Conversion Kit Installation in a Passenger Car..... 2-6

2-3. Typical LNG Conversion Kit Installation in a Passenger Car..... 2-8

2-4. Vehicular LNG System Schematic..... 2-9

2-5. CNG Cylinder and Stored Gas Weight Versus Cylinder Volume..... 2-16

2-6. Three-Stage Pressure Regulator..... 2-22

2-7. CNG Fleet Fueling Station..... 2-32

2-8. Typical LNG Fleet Fueling Station..... 2-35

3-1. Natural Gas Performance at Higher Compression Ratios in a Single-Cylinder Engine..... 3-5

3-2. Relative Fuel Economy and Research Octane Number Requirement of Spark-Ignition Engines as a Function of Compression Ratio..... 3-6

3-3. Emissions Characteristics of a Single-Cylinder Engine with Gasoline and Natural Gas..... 3-7

3-4. Effect of Ignition Timing on Fuel Consumption and Exhaust Emissions with Natural Gas..... 3-8

3-5. Effect of Equivalence Ratio on Thermal Efficiency and Relative Power in a Single-Cylinder Engine with CNG..... 3-9

5-1. Fuel Economy Shortfalls between EPA Test and In-Use Data..... 5-5

5-2. Projected Petroleum Fuel Consumption for Private and Commercial Trucks..... 5-20

5-3. Projected Petroleum Fuel Consumption for Trucks in Fleets of Six or More..... 5-21

6-1. United States Proved Natural Gas Reserves, 1971 to 1981..... 6-6

FIGURES (Continued)

7-1. Example Car Body Design Using Collapsible Body Sections to Enhance Impact Safety..... 7-38

8-1. Compressor Cost versus Compressor Capacity..... 8-5

8-2. User Economics of Natural Gas as a Vehicle Fuel - Scenario 1..... 8-6

1. INTRODUCTION

The goal of energy independence leads inevitably to a search for alternative highway vehicle fuels which can be produced from domestic resources in sufficiently large quantities. Natural gas (NG) is one such fuel. Extensive foreign and domestic experience has shown that NG can be used in conventional vehicles without major engine modifications. NG is currently available in large quantities, it is distributed nationwide through a million-mile pipeline network, and it clearly warrants consideration for a wider role as an automotive fuel.

On December 12, 1980, Public Law 96-512, the Methane Transportation Research, Development, and Demonstration Act of 1980, was signed into law. Its primary purpose is to initiate an active program under the direction of the Department of Energy (DOE) to enhance the utilization of methane fuel in automotive fleet vehicles and farm equipment. The term methane, as used in this report, includes and is interchangeable with NG derived from any resource, provided methane is the predominant constituent. In anticipation of its expanded role, the DOE Office of Vehicle and Engine R&D conducted a workshop in August 1980 to identify pertinent topics for the assessment of methane as an automotive fuel. That workshop formed the basis for this study.

This report, prepared by The Aerospace Corporation for the Office of Vehicle and Engine R&D of the DOE, assesses issues pertinent to the supply and use of methane-related fuels in highway-vehicle spark-ignition (SI) and diesel, or compression-ignition (CI), engines. In addition to NG derived from the earth, synthetic (or substitute) natural gas (SNG) derived from coal, wood, and solid waste, is considered. Methanol is also considered because it can be derived from either NG or the same sources as SNG and because it is a liquid fuel at ambient conditions. Topics covered in this report include fuel system technology, vehicle operation, resource energy utilization, potential petroleum displacement, fuel supply, vehicle safety, user economics, and research

needs. The assessment is intended to satisfy the requirements of Section 7(a) of the Act. Evaluations of institutional barriers, other alternative fuels, and alternative petroleum displacement options were not included in this study contract.

The approach selected for this study featured an extensive review of the open technical literature, supplemented by numerous discussions with manufacturers of NG systems and components, fleet operators, researchers, and government personnel. In addition, two late-model automobiles, equipped with SI engines and converted to compressed natural gas (CNG) operation, were tested to determine their performance, fuel economy, and exhaust emissions relative to operation on gasoline. During the course of this effort, three bimonthly meetings were conducted to inform interested industry and government organizations of study progress, and to solicit technical information for use in the study.

The report is divided into three volumes, of which this is the second. Volume I, Executive Summary, summarizes the results of the study. This volume, Volume II, is entitled Technical, Supply, and Economic Assessments. It documents in detail all study efforts and results. Volume III, Appendices, provides supplementary data and evaluations. It includes detailed discussions of fuel properties; fleet performance, fuel economy and emissions data; and unconventional gas sources. Also included are the comments submitted by two organizations after their review of the draft report. Where appropriate, review comments are reflected in the final version of the report.

This volume of the report consists of nine sections. Section 2, Fuel System Technology, describes the types of CNG and liquefied natural gas (LNG) systems developed to date. Both vehicle and refueling station hardware are included. Fueling station cost is examined, and the cost, weight, packaging, and other implications of vehicle conversion to NG are discussed. Methanol systems are also addressed, in less detail.

Section 3, Vehicle Operation, examines the fuel economy, emissions, and performance of vehicles using NG and methanol fuels. Theoretical considerations, laboratory data, and fleet experience are summarized.

Section 4, Resource Energy Utilization, analyzes the efficiencies for each major step in fuel production from resource extraction to the vehicle tank. Vehicle energy requirements are then analyzed, followed by a discussion of overall resource energy consumption from resource extraction through fuel utilization.

Section 5, Potential Petroleum Displacement, analyzes domestic fleets of cars, trucks, and buses to identify sectors of those fleets amenable to NG and methanol use. Projections of the total quantities of gasoline and diesel fuel required by fleet vehicles are made through the year 2000, and the amount potentially displaceable by NG and methanol is evaluated.

Section 6, Fuel Supply, examines the natural gas and methanol supply prospects for the next two decades, and reviews the technology for production of NG and methanol from several raw material sources. In addition, recent projections of supply, demand, and prices from several literature sources are summarized.

Section 7, Vehicle Safety, examines the safety of NG and methanol vehicles relative to conventional vehicles. Hazards of fuel systems in normal vehicle operation and under accident conditions are addressed, as well as environmental and health hazards.

Section 8, User Economics, compares recent studies of NG user economics, and presents the results of a payback period analysis performed for this study.

Section 9, Research Needs, lists specific research needs in the areas of vehicle performance, fuel economy, and emissions; vehicle safety; and studies and assessments. These programs are needed to develop a sound technical data base that would encourage the expanded use of NG in the automotive sector.

SECTION 2

FUEL SYSTEM TECHNOLOGY

This section addresses the system hardware and supporting technology for use of natural gas (NG) and methanol in highway vehicles. Methanol is included because it is a liquid fuel which can be produced from NG or from the same resources as synthetic (or substitute) natural gas (SNG), and because it permits the use of relatively conventional fuel systems.

Subsection 2.1 describes the types of vehicular compressed natural gas (CNG), liquefied natural gas (LNG), and methanol conversion systems that have been utilized to date for spark-ignition (SI) engines. It also describes NG and methanol systems for possible use in compression ignition (CI), or diesel engines. In Subsection 2.2, component hardware technology is then discussed for each fuel system, and in Subsection 2.3 the weights, volumes, and costs of the systems are examined. Subsection 2.4 provides brief descriptions of CNG, LNG, and methanol vehicle fueling stations and examines their approximate costs.

The bulk of automobile, truck, and bus gaseous fuel conversions performed to date has involved the addition of CNG, LNG, or liquefied petroleum gas (LPG) systems to carbureted gasoline engines. The principal interaction between the conventional and alternative fuel systems is at the carburetor inlet, where a gas-air mixer usually replaces the air cleaner assembly, and at the fuel switchover controls. Approximately 275,000 private and fleet vehicles in Italy, and about 20,000 fleet vehicles in the United States presently use CNG. Several thousand vehicles in France, Canada, Iran, and other countries also use CNG, and New Zealand plans to convert 150,000 fleet and private vehicles to NG use by 1985. Currently, LNG is used in about 200 fleet vehicles in the United States. Approximately 700,000 Italian vehicles presently use LPG, as do numerous vehicles in other countries. Methanol is widely used

in race cars, and about 100 methanol fleet vehicles are currently being evaluated in California. LPG conversions and original equipment manufacturer (OEM) factory installations represent a growing trend in the United States, but one with probably more limited ultimate potential than NG, since most LPG is presently derived from NG processing. Consideration of LPG and other non-methane-related alternative fuels was not included in this study contract.

Methanol has been used in automotive engines in blends with unleaded gasoline, at concentrations of up to about 20 percent methanol, without harmful effects to engine or fuel system components suitably designed and constructed of the proper materials. However, blends will not be considered in this study, since the potential gasoline displacement is limited and system operation is already being evaluated in fleet tests. Furthermore, the use of neat methanol or other methanol-based fuels in dual-fuel systems will not be considered here, because methanol can be distributed, marketed, and used in essentially the same manner as other liquid fuels, making a dual-fuel approach unnecessary.

2.1 VEHICLE FUEL SYSTEMS

2.1.1 General Description

Two categories of alternative fuel systems, dual-fuel and single-fuel, are considered in this study. Vehicles converted to dual-fuel operation can operate on either the original fuel or the alternative fuel, whereas single-fuel vehicles are dedicated to operation with the alternative fuel. Dual-fuel systems for SI-engine-powered vehicles typically retain the original engine configuration and fuel system components, while adding a supplementary fuel system for CNG or LNG. A manual switch selects operation on either gasoline or NG. Conversely, in a single-fuel SI-engine system, many of the original engine and fuel system components are replaced for satisfactory operation with the alternative fuel, rendering operation on the original fuel impractical or impossible. For CI engines, the dual-fuel versus single-fuel distinction is not as clear-cut. For some systems under development, both fuels must be used

simultaneously in some or all operating modes, and operation on either fuel alone may not be possible, as discussed in more detail in Subsection 2.1.7.

2.1.2 Dual-Fuel CNG Systems for SI-Engine-Powered Vehicles

A CNG dual-fuel conversion system typical of those now commercially available in the United States is exemplified by the system of Dual Fuel Systems, Inc. (DFSI) of Culver City, California. The system is designed for carbureted SI engines, and systems of similar design are marketed by Essex Cryogenics of Missouri, Inc. (ECMI) of St. Louis, Missouri, CNG Services, Inc. (CNGS) of Pittsburgh, Pennsylvania and, reportedly, Dual Energy, Inc. (Refs. 2-1 through 2-4). A number of conversion kits have also been designed by foreign and domestic manufacturers and installed on their fleet vehicles. These are sometimes supplied to other potential users for evaluation purposes. During 1981, two additional domestic suppliers began marketing such systems--Gas Service Energy Corporation (GSEC) of Kansas City, Missouri, and Advanced Fuel Systems, Inc. (AFSI), of Wichita, Kansas.

CNG Fuel Systems, Inc. of Calgary, Canada, also markets a system utilizing equipment of Italian design and manufacture, including steel cylinders which do not currently meet United States Department of Transportation (DOT) safety requirements (Refs. 2-5 and 2-6). The principal differences between the various conversion system designs are as follows:

(1) Method of gas-air mixing--in a separate mixer or in the carburetor venturi.

(2) Pressure regulator design--two or three stages, separate or integral packaging, existence or type of provision for NG heating.

(3) Means of adjustment of the idle gas-air mixture.

(4) Provisions for fuel shutoff in the event of loss of electric power or manifold vacuum.

(5) Method for fuel switchover -- mechanical or electrical activation.

Although several Italian manufacturers produce high-strength steel cylinders, which weigh less than domestic units of conventional steel design, these do not meet DOT requirements for strength and pressure relief provisions (Refs. 2-7 and 2-8). Lightweight composite pressure vessels, constructed of a thin aluminum alloy shell overwrapped with reinforcing fibers, are reportedly being offered by CNGS for working pressures of 3000 and 3600 psi (Ref. 2-1). Most CNG system vendors also offer compatible CNG fueling station equipment. These systems are discussed in Subsection 2.3.

The only equipment known to have obtained Environmental Protection Agency (EPA) acceptance, by satisfying the State of California Air Resources Board (CARB) requirements for no significant emissions increase, is the DFSI system. However, the EPA is not presently regulating NG conversions, but relies instead on state controls.

About 20,000 vehicles worldwide have been equipped with the DFSI system, which has not changed greatly in design since its introduction in 1969. The DFSI system is shown schematically in Figure 2-1 (Ref. 2-9). It consists of one or more steel CNG storage cylinders, high-pressure tubing which leads to a first-stage pressure regulator, a solenoid shutoff valve, a second-stage low-pressure regulator, and a flexible hose which provides gas (at a pressure of less than 0.5 inches of water) to a gas-air mixer (sometimes called a natural gas carburetor). The kit also includes a fuel pressure gauge, and a manual fuel selection device which can be operated by the driver. Initially, the tanks are loaded to about 2400 psi through an engine compartment fill connection. For passenger car conversions, the cylinders are usually trunk-mounted. A selection handle activates CNG or gasoline solenoid valves, allowing only one to be open. Fuel switching in most cases can be accomplished while driving and without stalling. Transition times are acceptable under most conditions. A switch which senses intake manifold pressure shuts off the CNG whenever the engine is stopped. This safety provision is bypassed during engine startup.

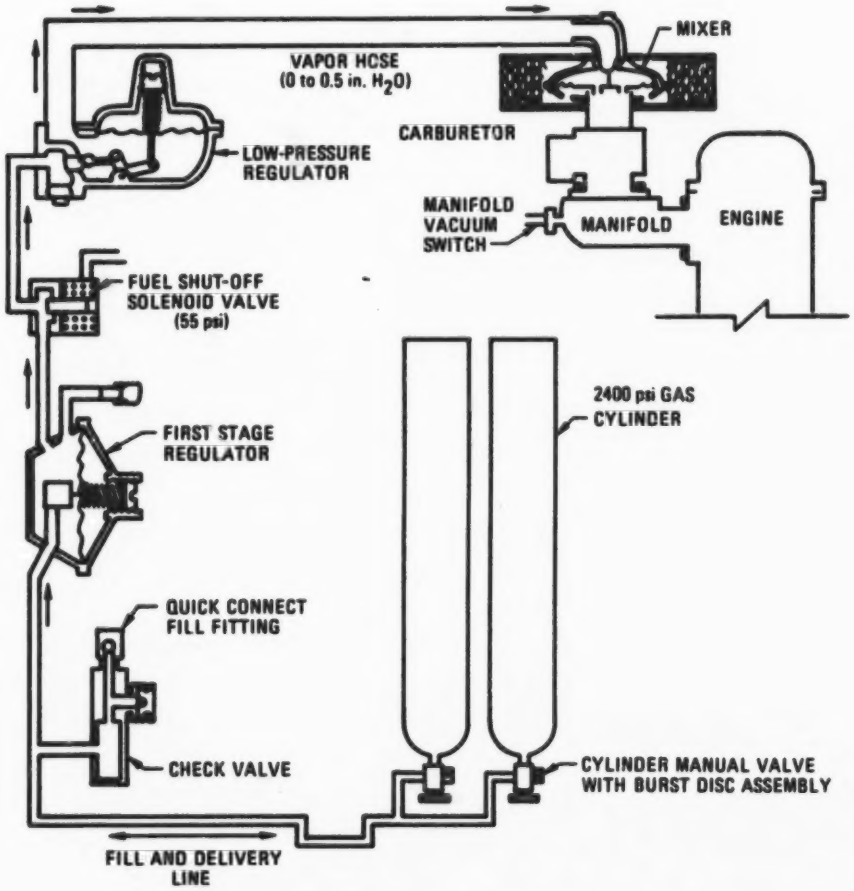

Figure 2-1. Vehicular CNG System Schematic (Courtesy of Dual Fuel Systems, Inc.)

A similar CNG system is produced by GSEC and is shown installed in a passenger car in Figure 2-2 (Ref. 2-10). Fueling is through a quick-disconnect fitting at the front end of the vehicle, sometimes under the hood. Two or more high-pressure cylinders are mounted in the trunk, preferably above the rear wheels, and are charged to a pressure of approximately 2400 psi. The exact pressure is determined by the fueling station so that approximately the same gas quantity ends up in the cylinders regardless of ambient temperature. In operation, CNG exits

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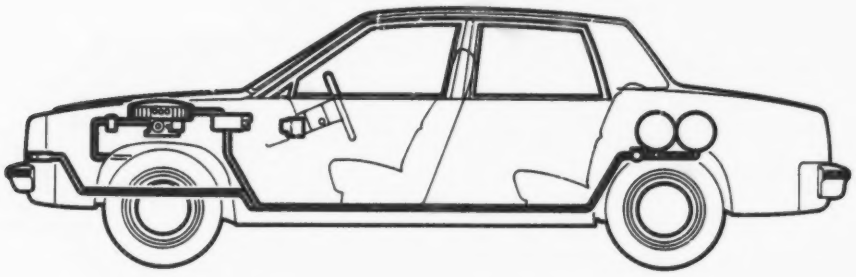

Figure 2-2. Typical CNG Conversion Kit Installation in a Passenger Car (Courtesy of Gas Service Energy Corporation)

all cylinders simultaneously through their manual shutoff valves and common manifold. Sometimes a master manual valve is also used. The gas next passes through the high-pressure line to the pressure regulator assembly. Two or three stages of regulation reduce the CNG to near-atmospheric pressure, and it is then delivered to a gas-air mixer, which is often mounted directly to the carburetor. The quantity of gas-air mixture delivered to the engine, and hence the power produced, is controlled by the accelerator pedal position. The fuel selector switch is usually mounted on the instrument panel.

At least two domestic CNG systems, those of GSEC and AFSI, employ a combination of domestic and Italian hardware (Refs. 2-11 through 2-16). The principal distinguishing feature of these systems is the use of proven three-stage pressure regulator assemblies manufactured by several Italian companies. These regulators are compact designs with a single housing, and use engine-coolant heating to prevent freezing of any moisture in the CNG. By contrast, the two DFSI regulators are separated by a solenoid valve and are unheated. DFSI recommends addition of small amounts of methanol to the CNG during compression to avoid possible icing in the solenoid valve or second-stage pressure regulator (Ref. 2-17).

Also significant is the AFSI method of fuel-air mixture preparation. The gas is fed directly to the carburetor venturis through two holes, typically drilled for that purpose, instead of being led to a separate gas-air mixer.

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The CNG cylinder(s) are normally attached to the vehicle by mounting straps or brackets in the trunk. Each cylinder has a manual shutoff valve and an automatic relief device sensitive to pressure and temperature rises. The cylinders typically have a storage capacity of 325 standard cubic feet (scf) (Refs. 2-12, 2-18, and 2-19). To prevent accumulation of any gas leakage into the trunk and the passenger compartment, a leakage barrier is generally installed. In the DFSI and GSEC systems, the dispensing end of the cylinder bank is enclosed in a tough flexible barrier material, which is connected both to the cylinders and to metal vents beneath the cylinders. Leakage discharged outside the vehicle dissipates rapidly.

2.1.3 Dual-Fuel LNG Systems for SI-Engine-Powered Vehicles

From 1968 through 1974, a number of LNG fleet conversions were performed by equipment manufacturers, gas utilities, and the General Services Administration (GSA). At present, however, there is only one large LNG-fueled car and light-duty truck fleet in operation, that of the Atlanta Gas Light Company (Ref. 2-20). Beech Aircraft Corporation (BAC) of Boulder, Colorado is an active developer and producer of conversion kits, and reportedly kits are also available from LNG Services, Inc. of Pittsburgh, Pennsylvania and other organizations (Ref. 2-1 and 2-21). The decline in usage is primarily attributed to limited availability of LNG, which is used, for the most part, only by utilities for peak-load shaving needs.

Other companies which have retained an interest in supplying LNG fuel systems if there is a resurgence of demand include ECMI (which will build to order), Kaiser Electro Precision (KEP) of Irvine, California, and Gibson Cryogenics (GC) of El Cajon, California (Refs. 2-3, 2-4, and 2-23).

The kits currently manufactured by BAC, and those previously manufactured by ECMI, KEP, and others are fundamentally similar (Refs. 2-2, 2-3, 2-4, 2-24 and 2-25). The BAC system, installed in a passenger car, is shown in Figure 2-3 (Ref. 2-22). Its principal components are (1)

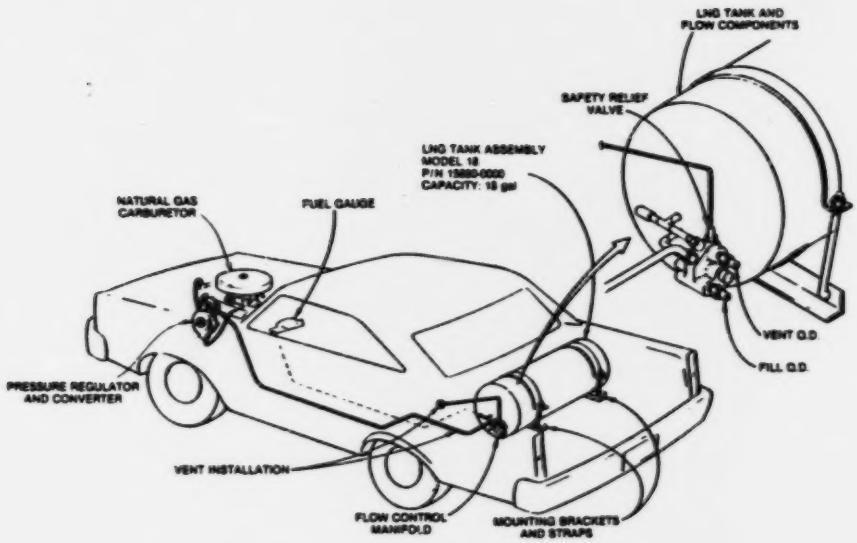

Figure 2-3. Typical LNG Conversion Kit Installation in a Passenger Car (Courtesy of Beech Aircraft Corporation)

a double-wall, vacuum-insulated, trunk-mounted cryogenic LNG tank, (2) an attached valve assembly for fuel filling, venting, and withdrawal, (3) low-pressure fuel lines, (4) a pressure regulator/converter assembly, and (5) a gas-air mixer located in the engine compartment. In operation, the fuel is driven from the tank by LNG vapor pressure.

Another LNG system, which was produced by ECMI and used for a number of years in single- and dual-fuel cars and trucks, is shown schematically in Figure 2-4 (Ref. 2-2). It features a low-pressure, double-wall, cylindrical cryogenic liquid tank, which can be filled to 90 to 95 percent of its nominal capacity through a quick-disconnect valve. NG vapor from the tank is vented through another quick-disconnect valve back into the fueling station. During operation, NG can be removed from the tank either as a liquid, through an outlet at the bottom of the tank, or as a vapor, through an upper outlet, as selected by the flow control valve in response to tank pressure. A solenoid valve controls the admission of fuel into a pressure regulator/heat exchanger assembly, which delivers

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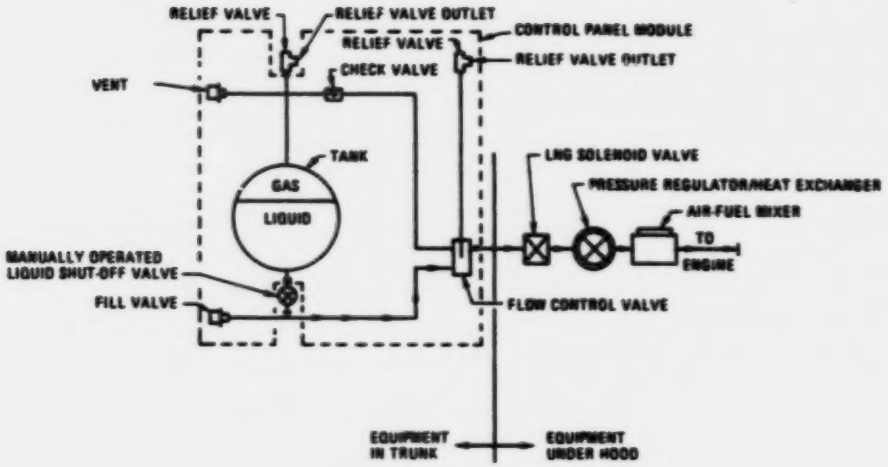

Figure 2-4. Vehicular LNG System Schematic
(Courtesy of Essex Cryogenics)

gaseous fuel at an acceptable temperature to the gas-air mixer. The mixer delivers a uniform fuel-air mixture to the carburetor, at a rate determined by the engine speed and accelerator pedal position. Pressure relief valves prevent destructive pressure buildup caused by excessive heat transfer to the LNG from the environment.

The LNG system designs of various vendors differ primarily in (1) the construction of the tanks to provide ruggedness, low boiloff rates, and reasonable cost, (2) the mechanization of liquid- or gas-withdrawal valves, depending upon pressure level and withdrawal rate, (3) the design of the pressure regulator/heat exchanger, and (4) the fuel-air mixer design. Tank operating pressures usually range from 5 to 60 psi. At pressures below about 20 to 40 psi, NG is withdrawn as a liquid, but at higher tank pressures withdrawal of vapor is necessary to reduce the tank pressure (Refs. 2-1 and 2-2). Tank pressures above approximately 60 psi result in automatic pressure relief to prevent tank rupture.

A heat exchanger is used to vaporize the LNG, if necessary, and to control the gas temperature entering the pressure regulator. It may utilize engine coolant, ambient air, or intake air as the heat

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source. The flow rate of the latter is approximately proportional to the fuel flow rate. Measurement of the tank liquid level is accomplished by a sensing unit, typically integral with the tank, which is electrically adapted to permit use of the existing fuel gauge.

As in CNG systems, a spark-timing advance from gasoline settings is desirable to maximize power and fuel economy. However, the amount of advance must be limited to provide satisfactory knock-free operation and emissions in the gasoline mode. Alternatively, a separate spark-advance device may be used to allow optimum timing for each fuel. Atlanta Gas Light Company uses fixed amounts of spark advance on its dual-fuel fleet of 120 cars, service vans, and medium trucks, and reports substantial engine knocking in the gasoline mode. However, emissions on LNG are within the State of Georgia emission certification standards introduced in 1981 (Ref. 2-20). BAC utilizes a spark-advance device in its LNG system currently under development (Ref. 2-22).

2.1.4 Single-Fuel CNG Systems for SI-Engine-Powered Vehicles

A single-fuel CNG conversion kit could in principle be based on existing dual-fuel kits. However, such conversions are not generally performed, and no kits specifically designed for single-fuel CNG conversions are known to be commercially available. The reason for this is the size of the CNG cylinders required to provide acceptable driving range. As discussed in more detail in Subsection 2.3, steel CNG tankage weighing more than 200 lb is required for a typical passenger car to achieve a range of 60 to 120 miles, and the space occupied by the tanks represents a large fraction of the trunk space. The weight problem could be lessened by the use of lightweight composite tank designs, but volume requirements would not be reduced, and several sources indicate that costs might be increased (Refs. 2-26 and 2-27).

If a single-fuel CNG system were to become available, it would probably differ from the previously described dual-fuel systems primarily in the following areas:

(1) The gasoline system, including tank and carburetor, would be removed.

(2) Engine compression ratio, spark timing, and other engine parameters would be optimized for NG.

(3) Lightweight CNG cylinders would be employed, and some would be mounted in the space formerly occupied by the gasoline tank.

A single-fuel demonstration vehicle, using lightweight composite CNG cylinders (spun aluminum/glass fiber wrapped), has been built by Ford Motor Company, using available, aircraft-quality, small-size cylinders in a Ford Escort (Ref. 2-28). In this installation, three identical cylinders are located beneath the vehicle, replacing the gasoline tank, and two of another size are trunk-mounted. No data on the performance of this vehicle are available (Ref. 2-29).

2.1.5 Single-Fuel LNG Systems for SI-Engine-Powered Vehicles

A single-fuel LNG conversion kit is essentially the same as a dual-fuel kit, except that fuel switching provisions can be deleted and engine parameters such as spark timing can be more fully optimized for NG operation. Although LNG tanks are bulkier than gasoline tanks of equal energy capacity, a comparable driving range can be provided with LNG at the expense of much of the trunk volume, as discussed in more detail in Subsection 2.3.

As is the case with CNG, a kit specifically designed for optimized single-fuel operation would probably feature hardware to increase engine compression ratio and to take advantage of the space freed by removal of the gasoline system. Such kits are not known to be commercially available at the present time, but as previously noted, existing dual-fuel kits are readily adaptable to nonoptimized single-fuel conversions.

Two single-fuel LNG automobile conversions, a Mercury Zephyr converted by Ford Motor Company and a Pontiac Phoenix converted by BAC, have been recently displayed (Refs. 2-21 and 2-28). The experimental Zephyr uses a 2.3 liter 4-cylinder engine, with the compression ratio

increased to 14 by using special pistons, and with the initial spark timing advanced. The trunk-mounted LNG tank has a capacity of 18 gallons. All cryogenic equipment, including the liquid feed system but excluding some external plumbing, was provided by BAC. The Phoenix is a 1980 model equipped with a 2.8 liter V-6 engine and a 4-speed manual transmission, using the same LNG tank and feed system design as the Zephyr (Ref. 2-28). The fuel system installation differs from that in the Ford vehicle primarily in the details of the plumbing and the lack of isolation between the passenger compartment and the tank. Two 3-in^2 vents are located on either side of the car near the roof level, and the stock fuel gauge has been adapted to indicate LNG quantity. This, or a similar car, has apparently been tested for fuel economy and emissions by Mercedes Benz in Denver, using different spark timing (Ref. 2-21). Endurance tests, consisting of both city and highway driving, have been conducted by BAC on the vehicle. With a fully loaded fuel tank and optimal spark timing, driving ranges as high as 386 miles have been reported.

2.1.6 Single-Fuel Methanol Systems for SI-Engine-Powered Vehicles

Single-fuel methanol conversions are commercially available from Alcohol Conversions, Ltd. (ACL) of Sunnyvale, California. ACL is a subsidiary of Alcohol Energy Systems, Inc. of Sunnyvale, California, which has participated in about 50 methanol conversions to date and is monitoring and maintaining a state fleet of about 50 vehicles (Ref. 2-30). In these conversions, the existing vehicle fuel tank is used, but in vehicles which use terne-plated tanks the terne (lead/tin) plating is removed. The fuel filter, fuel pump, sealing elements, and carburetor float are all replaced with units constructed from different, methanol-compatible materials. Aluminum carburetors are chrome plated to protect against corrosion, and new, larger jets are installed. A vaporizer/heater heats the fuel-air mixture in the intake manifold, using engine coolant, exhaust gas, or an electric heater as the heat source. Colder spark plugs are installed, and both initial spark timing and the spark advance curve are altered for improved performance and fuel economy. In some conversions,

the engine compression ratio is increased by using new pistons or milling the head, or a turbocharger is added.

Conversions have also been performed in support of a 112-vehicle fleet evaluation in California, using modified Ford Escort station wagons and Volkswagen Rabbit automobiles and pickup trucks (Refs. 2-29, 2-31, and 2-32). The Ford vehicles are equipped with 1.6 liter 4-cylinder engines, with the compression ratio increased from 8.8 to 11.4 to improve performance and fuel economy. To avoid corrosion problems, electroless nickel plating was applied to the fuel tank and carburetor body, dichromate coating was applied inside the fuel pump housing, and steel fuel lines were replaced first by nylon lines and then by lines produced from stainless steel. The carburetor jets were enlarged to accommodate higher fuel flow rates, and the ignition timing was changed. Five percent of isopentane is being added to the methanol to obtain satisfactory cold-starting and acceptable driveability (Refs. 2-29 and 2-33). The Rabbits also have 1.6-liter 4-cylinder engines. The fuel injection system was equipped with enlarged orifices and additional cold-start injectors, and engine compression ratio was increased to 12.5 (Ref. 2-32).

2.1.7 Systems for Diesel-Engine-Powered Vehicles

High-octane fuels like NG and methanol have a correspondingly low ignition quality, and are not suitable for direct use in unmodified conventional CI engines. However, in principle these fuels can be used in CI engines if ignition aids are employed. The ignition aids can be chemical fuel additives, spark plugs, glow plugs or other heated surfaces, or pilot injection. In the latter case, a small amount of diesel fuel is injected into the cylinder, where it ignites and touches off the primary fuel-air charge. Two fuel systems are therefore required with pilot injection, and operation solely on the alternative fuel is not possible. Because of the difficulty in achieving satisfactory operation of CI engines with NG or methanol over a wide range of operating conditions, there are no commercially available conversion kits for vehicles and there is limited vehicle experience. Conversions are, however, available for

stationary engines. The fuel supply systems would not differ substantially from these previously discussed for SI-engine vehicles, but engine-related changes might be substantial. The following subsections briefly discuss the engine modifications which could be used in principle. Laboratory systems and available data are covered in Section 3.

2.1.7.1 Compressed Natural Gas

In principle, conversion kits for CNG could use one of the following two approaches. Currently, only the first approach is considered to be practical. Fuel additives are not considered because no effective ones are known for NG.

(1) The CNG could be "fumigated," i.e., mixed with air in a mixer, or injected into the intake manifold. An ignition aid would still be required. In 1972, Mercedes Benz tested a diesel engine converted to SI operation (Ref. 2-34). Italian investigators have studied manifold injection in a 6-cylinder Fiat engine, using different pilot flow rates (Ref. 2-35). Wellington Gas Company of New Zealand and Tessari Company of Italy have equipped a 6-cylinder Ford diesel engine with an electronically-controlled governor, and have successfully operated the engine with 85 percent CNG (Ref. 2-8).

(2) The CNG could be injected directly into the cylinder during the compression stroke. Some form of ignition aid would be required. Although power could be increased compared with the first approach, the amount of CNG that could be withdrawn from the tanks would be substantially reduced because of injection pressure requirements of as much as 1000 psi. Southwest Research Institute has tested high-pressure CNG injection into a two-stroke Detroit Diesel 6V-71N engine modified to use spark ignition (Ref. 2-36).

2.1.7.2 Liquefied Natural Gas

The following two approaches might be used for LNG conversion kits for diesel engines The first is simpler, and the second offers higher power output. As with CNG, no effective fuel additives are known.

(1) The LNG could be vaporized, fumigated, and ignited with the help of an ignition aid, similar to the CNG system.

(2) The LNG could be pumped to a suitable pressure, vaporized, and injected directly into the cylinder during the compression stroke. One of the previously discussed ignition aids would be needed. Unlike the case with CNG, this approach allows full use of the NG tank contents, with only a small power drain for LNG pumping. Researchers at Cornell University and the Musashi Institute of Technology in Japan have successfully injected hydrogen into an engine cylinder near top dead center, using glow-plug ignition. However, hydrogen's ignition energy requirement is an order of magnitude lower than that of methane.

2.1.7.3 Methanol

The following approaches could be taken for the use of methanol in CI engines. As discussed in Section 3, most of these techniques have been demonstrated experimentally.

(1) Chemical additives such as hexyl nitrate can be employed. In virtually all cases, the fuel injection system would require replacement to handle flow rates up to double those with diesel fuel.

(2) Emulsions of methanol in diesel fuel can be used. In this case fuel injection system capacity increases might also be required.

(3) Other ignition aids can be employed, as previously discussed, in conjunction with either fumigation or direct injection of methanol.

2.2 COMPONENT TECHNOLOGY

2.2.1 Current CNG Tank Technology

The CNG storage system size and weight, and the resultant vehicle driving range, are the primary factors adversely affecting the acceptability of CNG in fleet vehicles. Steel cylinders designed to meet DOT Specification DOT3AA are intended for use in transporting industrial gases, including methane, but are not intended for use with NG or potentially corrosive gases (Ref. 2-7). However, 10-inch diameter, 2400-psi operating pressure cylinders designed to comply with DOT3AA specifications are widely used with NG. They are sufficiently overdesigned that at 130°F they can be filled to 1.25 times their normal operating pressure at 70°F,

allowing them to be filled to their rated contents at the higher temperature. They are substantially heavier than the more highly stressed cylinders made in Italy for vehicle use (Refs. 2-6 and 2-7). Figure 2-5 compares cylinder and stored-gas weights as a function of cylinder volume. The lengths of the DOT cylinder and several of the Italian cylinders manufactured by Faber of Udine, Italy, are noted on the curves (Refs. 2-6, 2-9 and 2-35).

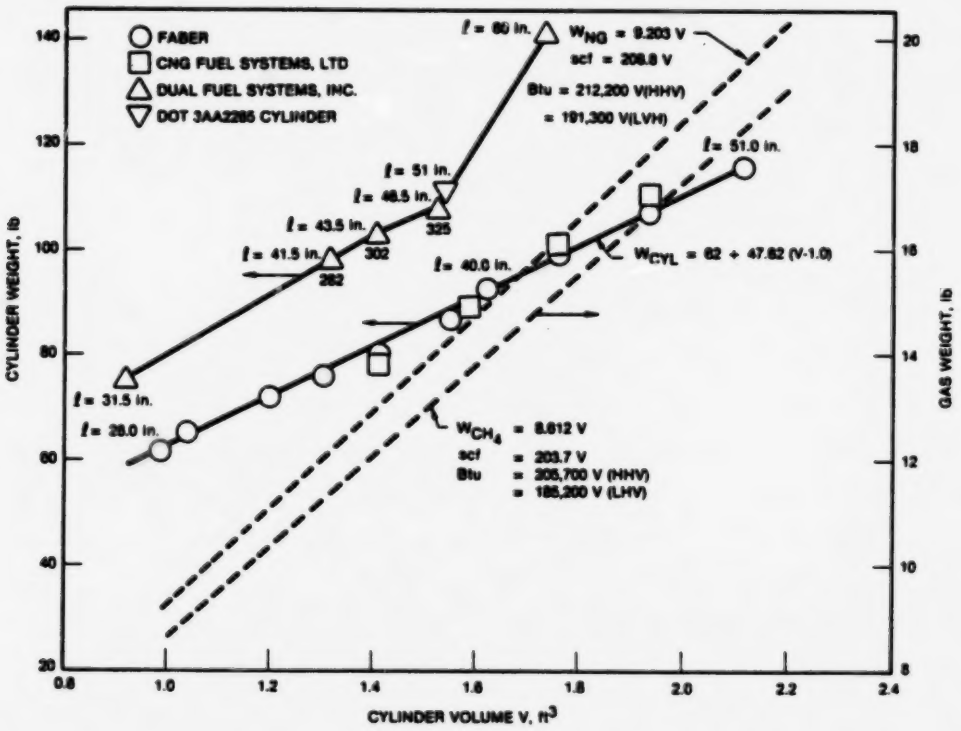

Figure 2-5. CNG Cylinder and Stored Gas Weight versus Cylinder Volume

2.2.2 Lightweight CNG Tank Technology

Both domestic and foreign CNG kit marketers have considered lightweight cylinder designs, but only CNG Services, Inc., is known to be offering them currently. NCF Industries of Los Alamitos, California, reportedly plans to offer them in the near future (Ref. 2-37).

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For mobile applications, it is important to minimize the empty tank weight. For relatively thin-walled cylinders and spheres, it can be shown that the ratio of gas weight, W_G, to tank weight, W_T, is given by the equation

$$W_G/W_T = CS/\rho_T ZRT \qquad (2\text{-}1)$$

where:

C = shape constant, 0.5 for very long cylinders, 0.67 for spheres

S = allowable tensile stress at operating pressure

ρ_T = density of the tank material

Z = gas compressibility factor

R = gas constant

T = absolute gas temperature

As discussed in Volume III, Appendix A, CNG has its lowest compressibility factor at about 2400 psi. Therefore, the highest ratio of stored gas weight to cylinder weight is achieved at this pressure. There is latitude for some pressure increase, since the Z value increases only 1 percent at a pressure of about 2750 psi. If the emphasis were put on cylinder compactness, pressures higher than 2400 psi could be used, but corresponding fueling station modifications would be required.

Lightweight designs for automotive use, where cost is a major consideration, could include high strength steels, aluminum alloys, and composite structures. High strength steels are more costly and typically more difficult to fabricate, and they are often more susceptible to chemical attack. An important lesson in the potential difficulty of utilizing high strength steels in CNG service was learned from the explosion of a large seamless steel cylinder in an over-the-highway transporter in 1977, as discussed in Section 7 (Refs. 2-38 and 2-39).

Aluminum alloys have been used for pressure vessels, but their weight advantage relative to steel is only about 30 percent and costs are

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higher (Ref. 2-26). Welding is difficult and produces large heat-affected zones. However, aluminum is generally considered to be relatively immune to attack by hydrogen sulfide or other NG constituents (Ref. 2-40).

Composite pressure vessels, consisting of a metallic inner shell and a layer of reinforcing fibers such as fiberglass, or an organic polymer such as kevlar, offer a potential 50 percent weight reduction and other advantages (Ref. 2-26). The shell material can be chosen primarily for compatibility with its contents, and the overwrap can bear most of the pressure loads without any weakening from attack by the tank contents. The overwrap can be total, with fibers placed to resist stresses in both the hoop and polar directions, or it can be confined to the cylindrical section only. The latter approach is feasible because the stresses in the hemispherical dome are theoretically half of those in the cylindrical section.

The use of only hoop windings for shell reinforcement yields the most easily manufactured and least expensive composite cylinder. For a 325 scf hoop-wound cylinder, weight is estimated at 62 lb and, in high-volume production, a cost of about $200 is projected (Ref. 2-26). The material is more vulnerable to fire than steel, and special provisions are desirable. The bare aluminum alloy domes have an annealing temperature of 500°F to 600°F, resulting in potential cylinder failure at below-normal operating pressure in a fire situation. The domes are therefore thickened, to as much as twice the cylindrical shell thickness, to increase their heat capacity. Each end of the cylinder would be equipped with temperature- and pressure-sensitive relief provisions. The hoop-wound section of the cylinder is reportedly usable at temperatures of 1000°F to 1200°F, depending upon the materials and their thicknesses. The resin contributes little to the strength of a hoop-wound composite structure (Ref. 2-26).

Long fatigue life, ranging from 100,000 to 500,000 cycles, is claimed for composite vessels (Ref. 2-26). The composite structure is helpful in this regard since the metal shell is normally under compressive

stress in the absence of an internal pressure. When pressure is applied, the metal does not reach as high a tensile stress as it would in the absence of this preload, and the fibers can more readily accept the higher tensile stresses than the shell.

Another desirable feature of composite pressure vessels is the manner in which they fail when an internal crack propagates to the surface of the metal shell. Instead of bursting, such vessels merely leak into their supporting fiber structures. Detection of leaking gas or of hydrotest liquid is straightforward.

Conventionally wound fully wrapped composite pressure vessels have been built in sizes from 46 to 30,000 in^3 (Ref. 2-27). About 50,000 vessels with 2215 psi operating pressure have been built for firemen's breathing apparatus. They are rugged, and can be dropped 10 to 16 feet onto rigid steel plates while containing 3000 psi. The resin is affected by ambient temperatures as low as 140°F to 160°F, and vessel integrity problems are encountered above 250°F. Normal pressure relief provisions have proven adequate in fire tests. Tank support requires use of a thin layer of elastomeric material to avoid abrasion from clamping devices, and allowance must be made for tank expansion, which is about twice that for steel tanks (Ref. 2-27).

A glass-reinforced, aluminum-shell, composite-wound pressure vessel of about 300 scf capacity has been designed by Structural Composites Industries, Inc., for possible automotive CNG application. For an operating pressure of 3000 psi, the cylinder (9.9 in. diameter and 44 in. long) was estimated to weigh 57 lb and to cost about $250 for production runs of several thousand. The tank weight is approximately proportional to the product of pressure and tank volume (Ref. 2-27).

The damageability of composite pressure cylinders of automotive size under crash conditions has not been thoroughly evaluated (Refs. 2-27 and 2-41). Drop tests of smaller vessels, bullet penetration tests, and dragging of pressurized vessels behind vehicles indicate toughness and resistance to catastrophic failure. Fire tests have demonstrated success-

ful operation of pressure relief devices. Under crushing loads, thin aluminum liners may be separated from the overwrap and may crack, resulting in a gas leak, but probably no rupture. Bare aluminum domes can fail in the same manner as steel cylinders. The weakening of fiberglass structures by environmental humidity can be avoided by special paints (Ref. 2-41).

2.2.3 Adsorption System Technology

An alternative gas storage concept involves the adsorption of methane on molecular sieves or activated carbon particles at pressures in the 350 to 400 psia range. In addition, a small quantity of gas is present in the voids between particles. A preliminary analysis of the concept is presented here. In the analysis, a tank internal volume of 1.5 ft^3 was assumed, the same as for a typical high-pressure storage cylinder. Tank weights were estimated based on an assumed minimum wall thickness of 50 mils. Adsorbent property data were obtained from References 2-42 and 2-43.

The results of the calculations are shown in Table 2-1. The tank pressures listed for molecular sieves and activated carbon appear to be nearly optimum on the basis of system weight. Lower pressures provide little NG storage capacity, while higher pressures show only small incremental gains. The results indicate that, with current technology, stored

Table 2-1. Comparison of Gas Storage Methods

STORAGE SYSTEM	TANK PRESSURE, PSIA	WEIGHT, LB				WEIGHT RATIO, STORAGE SYSTEM TO GAS
		TANK(1)	ADSORBENT	STORAGE SYSTEM	GAS	
HIGH-PRESSURE TANK	2400	108	-	108	13.5	8.0
MOLECULAR SIEVES	387	17.3	61.2	78.5	4.7	16.7
ACTIVATED CARBON	350	17.3	45.9	63.2	4.1	15.4

(1) BASED ON 1.5 FT^3 TANK VOLUME.

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inert mass with an adsorption system would be about twice that of a current high-pressure steel cylinder, for a given stored gas mass. Furthermore, it has been tacitly assumed that cylinder pressure alone would supply a sufficient flow of gas. If engine exhaust heat were also needed to release the methane from the adsorbents, system complexity and weight would be greater.

Preliminary data on silica gels indicate that methane adsorption capability is significantly less than for either molecular sieves or activated carbon.

2.2.4 Pressure Regulator Technology

The principal CNG system vendor in the United States, DFSI, uses two pressure regulators separated by a solenoid valve, where the second stage is a conventional residential pressure regulator. The assembly also includes fill and check valves and a pressure burst disc to prevent overfilling (Ref. 2-9). ECMI uses the same basic design (Ref. 2-2).

Other domestic vendors use Italian regulators. GSEC has selected a Tartarini regulator (Refs. 2-13 and 2-44). AFSI kits include an Auto Italia regulator (Refs. 2-14 and 2-16), while CNG Fuel Systems Ltd. is marketing an Italian-built Renzo Landi regulator (Ref. 2-6). The Italian regulators differ from the domestic designs in (1) their use of three integrated stages in one housing, (2) hot water or electrical heating of the gas, (3) control of the third regulator stage by intake manifold vacuum and gas-air mixer suction, (4) a valve between second and third stages to increase gas flow at high demand, and (5) accumulation of high-pressure gas as an aid for engine restarting (Refs. 2-6, 2-13, 2-14, 2-16, and 2-34). Despite these features, which have evolved over four decades, Tartarini does not recommend starting an engine on NG at temperatures below freezing, because of icing susceptibility (Ref. 2-34). Both DFSI and various users of domestic systems have acknowledged regulator freezing problems under less severe conditions. Consequently, DFSI

recommends adding a small amount of methanol to the CNG leaving the compressor and most users follow this advice (Ref. 2-17).

The regulator used by GSEC is shown in Fig. 2-6. In addition to the single-housing design, the regulator incorporates separate solenoid valves for regulated NG flow for engine starting and normal running, hot water connections for interstage gas heating, a vacuum connection for automatic gas shutoff if the engine is not operating, and an idle flow adjustment screw.

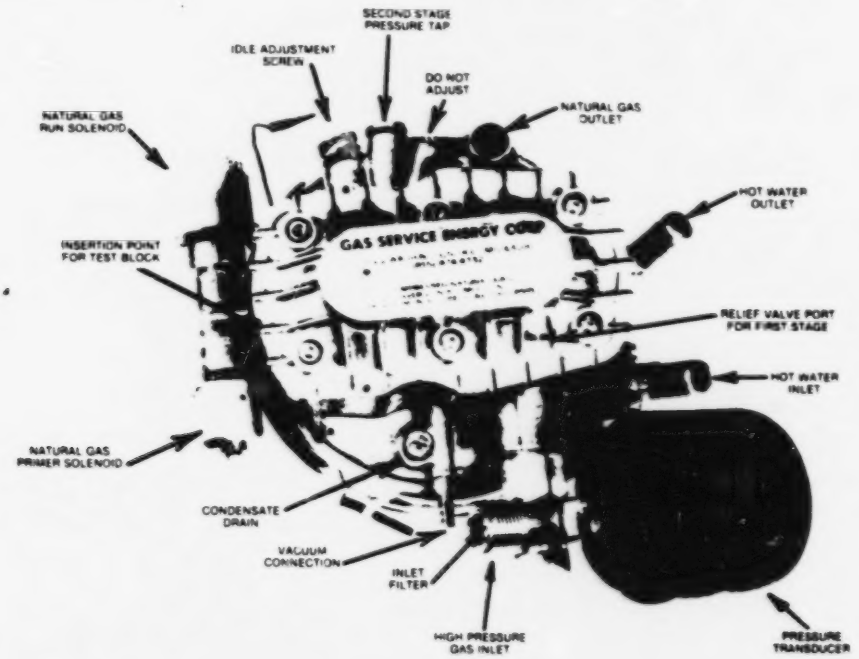

Figure 2-6. Three-Stage Pressure Regulator (Courtesy of Gas Service Energy Corp.)

2.2.5 Mixing Valves, Flow Controls and Safety Devices

The predominant gas-air mixer employed in the United States is a diaphragm-controlled, variable-venturi device which replaces the air cleaner. It is a modification of an Impco LPG gas mixer capable of use on SI engines up to 540 cubic inches displacement. Multiple gas mixers may be used for larger engines (Ref. 2-45). The mixer is mounted above the

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carburetor, if room permits, or more typically it is connected to the carburetor horn through an adapter tailored to the available engine compartment space.

The mixer is adjusted while the engine is running at light load, to produce a lean gas-air mixture with approximately 25 percent excess air. Generally, there is no provision for mixture enrichment at wide open throttle. At least one domestic marketer, AFSI, does not utilize a separate gas-air mixer, but instead admits gas through holes drilled into the venturi section of the carburetor. Information on the necessity for drilling is conflicting; apparently, existing carburetor passages may be usable in some instances (Refs. 2-15, 2-46, and 2-47).

Other elements of the gas-flow control system are hand-operated cylinder valves mounted on the CNG cylinders, vacuum switches for closing the gas solenoid valve when the engine stops, and mechanical/electrical or all-electrical switches to allow prompt transition from operation on NG to gasoline and vice versa. The manual cylinder valves incorporate a safety burst disc, backed up with a fusible plug. The latter melts at 212°F in the event of a fire and allows disc rupture at 3775 psi to preclude tank rupture (Ref. 2-9).

A safety device which has long been recommended, but is not generally used, is an excess-flow shutoff valve, which is intended to prevent complete discharge of the contents of a CNG cylinder in the event of a rupture in the high pressure line (Refs. 2-48 and 2-49). DFSI reports that such a device has not yet been satisfactorily designed. The principal problem is designing a device which will operate only when needed, and over the broad ranges of pressures and flow rates encountered in normal vehicle operation. Although excess-flow valves are useful for applications with nearly constant pressure and a moderate flow rate range, they have proven unsuccessful in automotive applications (Ref. 2-17).

2.2.6 Ignition Systems

One way to partially restore the power lost with CNG and LNG conversions is spark-timing advance, either by a fixed static adjustment

or by a device which advances timing only when the engine is operated on NG. Either the initial timing or the entire spark-advance curve may be changed. Manufacturers are offering such devices outside California, and users of CNG systems widely employ both static spark advance and various spark-advance devices to improve vehicle performance and starting. In all cases, the emissions impacts are either unknown or not advertised.

Since the 1975 model year, DFSI has consistently advised its customers against advancing spark timing beyond the engine manufacturer's recommended value. The objective is to prevent detonation, preignition, and emissions increases during engine operation on gasoline. Several electronics companies have designed add-on devices which employ dual spark-advance control to permit engine operation up to the point of engine knocking. One such company, Autotronic Controls Corporation (AT), has developed and tested a dual-spark device for CNG-powered engines. Based on test results, AT claims that its device, when properly installed on a vehicle, makes the vehicle more efficient without increasing emissions. AT feels that the EPA would be satisfied and offers the device for sale worldwide, except in California, for use in SI engines converted to CNG, LNG or LPG. Recently DFSI negotiated an agreement for exclusive distribution of the AT device for CNG systems, and now markets it for use outside California. DFSI intends to seek approval of the device in California and is also developing another unit. Various spark advance devices are currently being used by GSEC, APSI, and CNGS outside California (Refs. 2-15, 2-47, 2-50, and 2-51). Their performance from an emissions standpoint is uncertain.

The ignition needs of an LNG-fueled SI engine are basically the same as with CNG, except perhaps for greater spark advance to accommodate a cooler gas-air mixture. BAC currently uses a spark-advance device in its LNG conversion system, with acceptable emissions claimed (Ref. 2-21). Older conversion kits, used in the dual-fuel vehicles of the Atlanta Gas Light Company, employ a fixed spark advance that produces severe knocking when the vehicles are operated in the gasoline mode (Ref. 2-20).

2.2.7 LNG Cryogenic Tank Technology

The cryogenic tank is the heart of the LNG system, accounting for most of its volume, weight, cost, and operational constraints. It features double-wall construction, with the inner shell thermally isolated from the outer shell as much as possible, within economic constraints. Carefully designed structural supports and fluid piping are used to minimize thermal conduction, a high vacuum minimizes thermal conduction and convection, and a multilayer super-insulation minimizes radiation heat transfer. Normal heat leaks in the absence of fluid withdrawal cause continuous vaporization and tank pressure rise. If neither vapor nor liquid is removed, for example, when a vehicle is parked for a weekend or is being repaired or maintained, liquid boiloff will cause the pressure to rise, slowly approaching a point where vapor must be removed to preclude inner tank rupture (Ref. 2-20). BAC reports over a 14-day standby condition with a full tank without pressure relief (Ref. 2-21).

Domestic manufacturers of automotive LNG tanks include BAC, ECMI, KEP, and others, but only BAC is known to be fabricating such tanks currently (Ref. 2-21). ECMI (which will build to order), KEP, and Gibson Cryogenics are prepared to reenter the market if it expands sufficiently (Refs. 2-3, 2-4, 2-23, and 2-25). The domestic designs are typically cylindrical with elliptical heads. Tank capacities have ranged from 18 to 70 gallons. The weight and dimensions of ECMI's tanks are shown in Table 2-2 (Ref. 2-24). The 18-gallon tank used by BAC in its Pontiac Phoenix vehicle weighs the same as the 18-gallon ECMI tank (Ref. 2-22). The development of the BAC tank is documented in Reference 2-52.

In addition to the work of domestic suppliers, the German organization DFVLR has developed squat, oblate spheroidal tanks for automotive liquid hydrogen (LH_2) use, utilizing several construction materials. The DFVLR work has been well documented, including the information contained in a 1978 survey report prepared for DOE (Ref. 2-53). This technology could be applied to the less severe LNG application.

Table 2-2. Physical Characteristics of ECMI Cryogenic Tanks (Ref. 2-24)

LIQUID CAPACITY, GAL	OUTSIDE DIAMETER, IN	DOME-TO-DOME LENGTH, IN	EMPTY WEIGHT, LB
18	14.0	41.0	75
24.5	15.0	46.0	96
46	22.0	40.0	153
70	22.0	58.0	236

The principal differences between the domestic tank designs are the method for supporting the inner tank from the outer tank and the number of layers of super-insulation. Such features directly affect tank cost and crashworthiness. LNG tanks are more susceptible to internal damage and penetration than CNG tanks, and should rupture with less violence, but release much more fuel energy.

It should be noted that researchers at the Musashi Institute of Technology in Japan have developed a compact cryogenic pump for installation in an automotive LH_2 tank (Refs. 2-54 and 2-55). This electrically driven unit enables liquid, at pressures much higher than the tank pressure, to be vaporized and fed to a medium-pressure injection system for direct injection into the engine cylinders. This approach has allowed significant power increase over normal gasoline engine performance as verified in road tests of several cars. A high-pressure LH_2 pump for use in high-compression ratio engines is under development.

2.2.8 LNG Vaporizers and Pressure Regulators

In a typical system, when liquid fuel is removed from the LNG tank, a heat exchanger or vaporizer must be used to provide the 219 Btu/lb required for vaporization, and the sensible heat required to raise the vapor temperature from -259°F to a temperature of about 32°F. The final temperature of the gas-air mixture must be above 32°F to prevent icing. With vapor withdrawal, the heat exchange requirements are less. Available

heat sources are the engine coolant, engine exhaust, ambient air, and engine intake air. The temperature differential between the engine coolant and the LNG, even with a cold engine, is sufficient for vaporization. Normal operation of the vehicle with proper coolant level and antifreeze concentration will prevent any freeze-up. Once an engine is started, its exhaust could quickly provide abundant heat, but several problems have been encountered in matching heat flow to vaporizer requirements (Ref. 2-56). Ambient air could be provided by a fan, even before engine cranking, which would result in air-fuel mixture temperatures slightly below ambient. This is favorable for high volumetric efficiency and for accurate gas-air mixing. However, the use of atmospheric air for LNG vaporization might result in heat exchanger icing (Ref. 2-56).

The pressure reducer has a relatively simple function, comparable to that of the second stage of a CNG regulator, since it normally operates with an inlet pressure below 60 psi. It provides gas at near-atmospheric pressure to a mixer which may be identical to that used in a CNG system.

2.2.9 LNG Mixing Valves, Flow Controls, and Safety Devices

Current gas-air mixing valves and gaseous fuel induction techniques should be equally suitable for CNG and LNG systems. Fuel flow control is more complex with LNG, since both vapor and liquid phase withdrawal are usually provided. The flow control valve, however, can be simply a phase selector valve which responds to tank pressure. Above a preset value of about 20 to 40 psig, it would operate in a vapor withdrawal mode. Otherwise it would deliver liquid to the solenoid valve ahead of the heat exchanger (Ref. 2-2). The BAC system entrains vapor in the liquid feed above the pressure set point, which reduces tank pressure but maintains vehicle performance.

LNG systems include a manual shutoff valve similar to that of CNG systems, and several pressure relief valves of much lower pressure setting. The relief valves must be properly designed to prevent icing.

2.3 SYSTEM WEIGHTS, VOLUMES, AND COSTS

Detailed system weight data were provided by DFSI for its CNG system (Refs. 2-9 and 2-45). These data are presented in Table 2-3, along with an estimated LNG system weight breakdown based upon the previously described 18-gallon tank and the similarity of specific components. Necessary tank supports are included, but no allowances are made for possible suspension system changes, such as added rear spring leaves and heavier shock absorbers, or the use of a gas leak detector or spark advance device. For single-fuel conversions, the net vehicle weight effect is less than shown in Table 2-3, because of the weight savings from deletion of the gasoline system. The LNG system is approximately 100 lb

Table 2-3. Weights of Typical Natural Gas Systems for Light-Duty Vehicles

SYSTEM COMPONENT[1]	WEIGHT, LB CNG	WEIGHT, LB LNG
ENERGY STORAGE		
TWO 325 SCF STEEL CYLINDERS	216	-
ONE 18 GAL STEEL CRYOGENIC CYLINDER	-	75
OTHER HARDWARE		
MOUNTING BRACKETS	10	10
PRESSURE REGULATOR & SOLENOID VALVE	15	15
HEAT EXCHANGER	-	
GAS-AIR MIXER & CARBURETOR ADAPTER	10	10
FUEL GAUGE AND SWITCH ASSEMBLY[2]	2	1
LINES, FITTINGS, VALVES & CONNECTORS	2	2
TOTAL OTHER	39	38
FUEL	29	64
TOTAL	284	177

(1) VEHICLE RANGE TYPICALLY 60-120 MI FOR CNG (IN ADDITION TO GASOLINE RANGE IN DUAL-FUEL VEHICLES), AND 200-400 MI FOR LNG.
(2) DUAL-FUEL SYSTEMS ONLY.

lighter than the current CNG system, primarily because of tank weight differences, and provides about three times the operating range of the CNG system because of the greater fuel storage capacity. It is therefore more suitable for single-fuel vehicle conversions than CNG.

Weight and size data for current CNG and LNG tanks as a function of tank capacity are presented in Figure 2-5 and Table 2-2. Since fuel tanks are the dominant items in CNG and LNG systems, a comparison of energy storage characteristics relative to liquid fuel systems is shown in Table 2-4. The LNG tank is assumed to be filled to 95 percent of capacity to provide some startup gas and to allow for pressure buildup due to heat leaks. Systems in development may allow filling to within 2 or 3 percent of capacity (Refs. 2-21 and 2-29). Table 2-4 shows that the low densities of gaseous fuels result in low energy densities based on outer tank volume. In addition, LNG tanks do not effectively scale down to low capacities because of insulation requirements, and tanks do not readily adapt to the shape of the available space. Methanol's low heating value

Table 2-4. Fuel and Storage Tank Parameters

PARAMETER	GASOLINE	DIESEL FUEL	CNG[1]	LNG[2]	METHANOL
FUEL DENSITY					
LB/GAL	6.09	7.26	-	3.58	6.64
LB/CU FT	45.55	54.3	9.45[3]	26.8	49.7
LB/SCF	-	-	0.0445	0.0424	-
FUEL ENERGY (LOWER HEATING VALUE)					
BTU/LB	18,900	18,400	20,800	21,520	8,570
BTU/GAL	115,800	130,300	-	76,980	56,900
BTU/SCF	-	-	926	912	-
TANK FILL FRACTION	0.97	0.97	1.00	0.95	0.97
TANK OUTER VOLUME/INNER VOLUME	1.015	1.015	1.14	1.27-1.4[4]	1.015
FUEL ENERGY/TANK OUTER VOLUME, BTU/CU FT x 10^{-6}	0.824	0.960	0.172	0.43-0.380[4]	0.407
FUEL ENERGY/TANK WEIGHT, BTU/LB	14,250	14,500	2,450	11,060-9,990	6,580

(1) TYPICAL NATURAL GAS COMPRESSIBILITY FACTOR = 0.778 AT 2400 PSI PRESSURE AND 60°F TEMPERATURE
(2) PARAMETERS IN LNG COLUMN REFLECT PURE METHANE.
(3) CNG DENSITY AT 2400 PSI AND 60°F.
(4) RATIOS FOR 70 GAL AND 18 GAL LNG CAPACITIES, RESPECTIVELY.

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is the dominant factor causing it to require more than twice the liquid mass and tank volume of either gasoline or diesel fuel for the same stored energy. Methanol's energy per unit tank volume is comparable to that of LNG, but on a mass basis methanol is inferior.

Dual-fuel CNG conversion kits with two cylinders increase light-duty vehicle driving range by roughly 60 to 120 miles, depending upon the vehicle and driving cycle, and are currently available from at least five domestic suppliers for $1100 to $1600, excluding installation, taxes, and freight costs (Refs. 2-4, 2-9, and 2-14). Installation labor varies from about 8 man-hours for pickup trucks to about 12 man-hours for a passenger car or van, adding roughly $150 to $250 to the conversion cost. With an 18-gallon cryogenic tank, LNG kit cost is estimated at $1500 to $1800, with an additional $150 to $250 for installation (Ref. 2-21). However, potential suppliers indicate that system cost depends strongly on the specifications for crashworthiness and standby time before venting. It should also be noted that these costs are for the initial conversion. Current conversion system components typically have a long lifetime, which allows much of the system to be transferred from old to new vehicles with minimal rework or replacement.

Single-fuel methanol conversions are available from at least one supplier at a cost of $1500 to $2200 (Ref. 2-30). Vehicle driving range is diminished by 35 to 50 percent, while weight and volume are essentially unchanged unless a larger fuel tank is employed.

In the near future, CNG and LNG systems are expected to become lighter through the use of lightweight composite CNG cylinders, and aluminum alloy LNG tanks of possibly optimized shape for vehicular application. For example, BAC reports that a system based on an 18-gallon LNG tank fabricated from 5083 aluminum alloy would weigh 112 lb fully fueled, which BAC estimates to be less than the weight of the gasoline system it replaces. Tank volumes will not be reduced significantly unless higher CNG cylinder pressures are used or greatly improved LNG tank insulation systems are developed. Other NG energy storage concepts, such

as adsorbents, will require a technical breakthrough to offer weight or volume advantages.

2.4 FUELING STATIONS

Most equipment manufacturers agree that safe and economical operation of currently available CNG and LNG fueling equipment can best be accomplished at fleet garages or large public stations with trained operators. In the United States, only the fleet approach has been used to date. However, in Italy approximately 220 public CNG fueling stations have been in use for many years, supplying CNG to about 275,000 converted vehicles owned by individuals and organizations. Domestically, public stations are being seriously considered by CNG Services, Inc., and others, but the number of CNG or LNG vehicles would have to increase substantially from current levels for this approach to achieve more than localized success. In addition, small compressors for possible home use are under development, but cost, efficiency, and safety issues remain key concerns.

2.4.1 CNG Fueling Stations

In the United States, two general approaches to CNG vehicle fueling are employed. Often available in the same station the methods are (1) slow-filling, or time-filling, of up to about 80 vehicles simultaneously from a high-pressure compressor, and (2) fast-filling of vehicles, one or two at a time, from a cascade of high-pressure cylinders previously filled by a compressor. Time-filling requires up to 14 hours, while fast-filling is typically accomplished in 2 to 5 minutes. Figure 2-7 shows the principal components of a typical combined system. The fast-fill section consists of one or more multi-stage compressors which deliver CNG at approximately 3600 psig to individual cascades. On command, a portion of the stored CNG is delivered to the vehicles in a controlled manner through a set of fill hoses. Typically, two vehicle filling positions are provided per cascade for rapid fleet fueling. The time-fill section of the station consists of a high-pressure manifold from the compressor to a number of fill-post or hose-drop assemblies which allow the simultaneous slow fueling of a large number of vehicles.

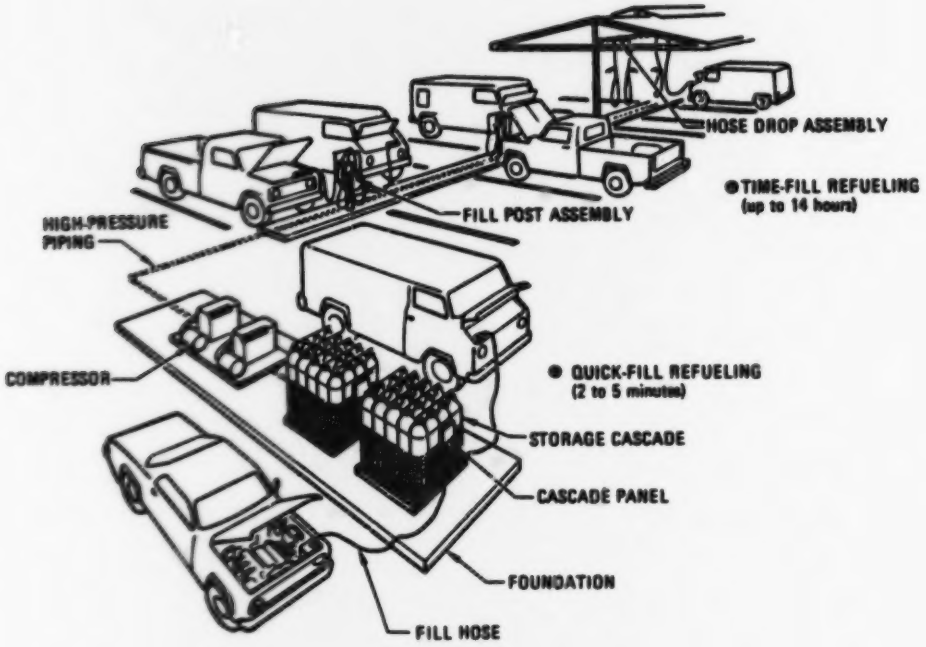

Figure 2-7. CNG Fleet Fueling Station (Courtesy of Dual Fuel Systems, Inc.)

The compressors are usually electrically driven, three- or four-stage machines which can achieve a 3600 psi output pressure when connected to a 1 to 5 psig NG distribution line. The fast-fill storage cascades typically consist of a group of 20 cylinders comparable in size to vehicle cylinders, but designed for an operating pressure of 3600 psi instead of 2400 psi. The higher pressure is needed to provide a significant pressure differential between cascade and vehicle tanks as filling nears completion. Automatic controls are provided on the cascades for selective discharge, progressing from the lowest pressure tanks to the high pressure tanks.

For the time-fill section, one or more compressors each supply a manifold, with the CNG regulated to a pressure which is ambient temperature-compensated to provide a consistent gas mass in the filled vehicle tanks. In the fast-fill section, the cascades are similarly controlled.

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Principal station design considerations are the number of CNG fillings required daily, the time available to perform them, available parking space, and equipment and facility costs. The compressor is the key component from the standpoints of initial cost, operating cost, and maintenance requirements. Current domestically marketed CNG compressors range in capacity from 3.5 to 100 scf per minute (scfm), which is equivalent to about 2 to 50 gallons of gasoline per hour. Smaller units are under development for use by small fleets or individual users. As shown in Table 2-5, compressor costs rise almost linearly with capacity from a minimum of about $5,000 up to about $70,000 at 100 scfm. Compressor ratings from different suppliers may not be comparable because of different assumed NG supply pressures and because sometimes an allowance is included for deterioration in capacity with time. Other items for which unit cost data are available are cascade cylinders at $350 each (10 in. diameter × 51 in. long) and high-pressure hose drops at $200 each. Station cost is affected by other factors, including the requirements for indoor or outdoor parking, electric power lines, barrier walls, and automatic leak detection equipment and controls. Total investment costs for a typical 40 to 50 scfm station range from $60,000 to $100,000. Recent fleet stations installed by the Southern California Gas Company have each cost approximately $100,000. They typically employ a 40 scfm compressor

Table 2-5. CNG Compressor Characteristics (Ref. 2-14)

MODEL	CAPACITY(1), SCFM	PRESSURE, PSIG INLET	PRESSURE, PSIG OUTLET	COST, DOLLARS
MAKO KA-7 CNG	7.5	1.5(2)	3600	$12,000
MAKO KA-15 CNG	17.3	1.5(2)	3600	17,000
NORWALK NQ-SV3	55	18	3600	37,000
MAKO	99.8	NA	3600	70,000

(1) DEPENDS UPON NATURAL GAS COMPOSITION.
(2) BUILT-IN REGULATOR REDUCTION FROM SUPPLY-LINE PRESSURE.

for slow filling of 60 to 80 vehicles, with one cascade of 20 cylinders provided for fast-filling of a small number of passenger cars. The compressor cost is about $50,000. The costs beyond those of the compressor, cascade, and hose drops or fill posts, are those associated with the underground high-pressure piping and the connections to the utilities (Ref. 2-57).

A cost estimate for a CNG station which can slow-fill 100 vehicles overnight and also fast-fill one vehicle at 15 minute intervals is given in Table 2-6. Compressor capacity is 30 scfm. The prices are in 1979 dollars, and do not include land, site preparation, or cost of obtaining building permits (Ref. 2-2).

Table 2-6. CNG Fueling Station Costs (Ref. 2-2)

ITEM	COST, DOLLARS
COMPRESSOR AND ASSOCIATED EQUIPMENT	$55,000
PAD FOR COMPRESSOR AND FAST-FILL EQUIPMENT	1,724
FAST-FILL SECTION EQUIPMENT	2,752
MISCELLANEOUS EQUIPMENT	16,173
SHELTER	4,500
FENCE	636
TOTAL	$80,785

2.4.2 LNG Fueling Stations

A typical LNG station consists of a bulk storage tank and its controls, a fuel transfer system, vehicle couplings, and a vapor disposal system. A fueling station such as that depicted in Figure 2-8 generally can fill several vehicles simultaneously from its LNG bulk storage tank. The latter can be periodically replenished through a vacuum-insulated pipeline from a liquefaction plant, or by truck or rail transport.

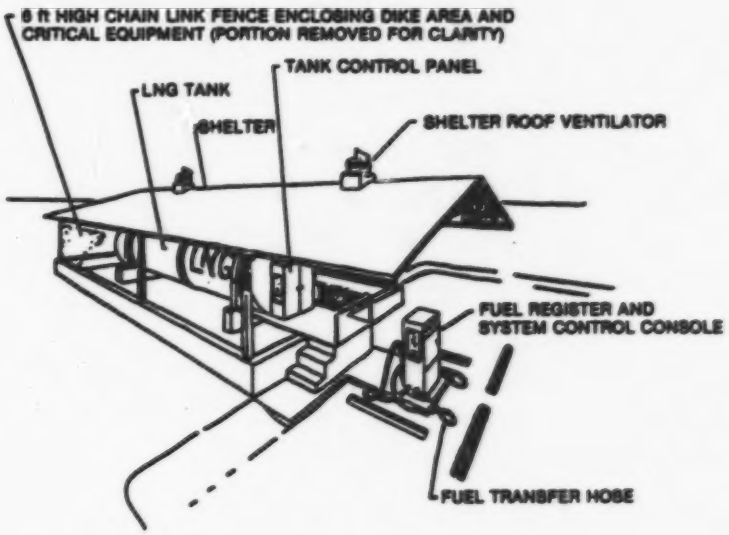
6 ft HIGH CHAIN LINK FENCE ENCLOSING DIKE AREA AND CRITICAL EQUIPMENT (PORTION REMOVED FOR CLARITY)
TANK CONTROL PANEL
LNG TANK
SHELTER
SHELTER ROOF VENTILATOR
FUEL REGISTER AND SYSTEM CONTROL CONSOLE
FUEL TRANSFER HOSE

Figure 2-8. Typical LNG Fleet Fueling Station (Courtesy of Essex Cryogenics of Missouri, Inc.)

Required tank volume depends on what is considered to be an acceptable refilling frequency. Alternatives for fuel transfer to the vehicle include the use of (1) pressure transfer, (2) an in-line pump, and (3) a pump submerged in the bulk storage tank. The pressure transfer system is the simplest and does not require electric power. However, it requires the highest tank pressure and creates the greatest problem of vehicle tank vapor disposal, since the vapors must be pressurized if they are to be returned to the bulk storage tank. For any fuel transfer system, vapor disposal can be a significant problem in the rare event that a warm, dry vehicle tank must be filled, requiring boiloff of a substantial fraction of the LNG load before normal operating temperature is reached.

The in-line pump allows low tank pressures, and so greater heat leakage into the tank can be tolerated before venting is required. It is more accessible than a submerged pump, allowing easier maintenance, servicing, and repair. During fueling, the pump provides enough pressure so that vehicle tank vapors can be returned to the bottom of the bulk storage tank, which aids recondensation. The pump, however, is exposed to

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ambient temperatures and must be cooled (primed) prior to operation. This operation vaporizes LNG which must be returned to the tank, and adds an unwanted increase in tank pressure.

The submerged pump method has some of the advantages of the in-line pump technique, including vapor recondensation, while avoiding the necessity of pump cooldown. It presents obvious difficulties when pump maintenance or repair are necessary.

Table 2-7 shows cost estimates for two LNG stations differing primarily in their storage tank capacities. The LNG storage tank is the principal contributor to fueling station cost. Unlike CNG stations, the cost of LNG stations declines slowly as fuel capacity is reduced. The prices shown are in 1979 dollars. They include a servicing island for simultaneously filling four vehicles but do not include land, site preparation, or building permits (Ref. 2-2).

Table 2-7. LNG Fueling Station Costs (Ref. 2-2)

ITEM	COST, DOLLARS	
	3125 GAL	10,600 GAL
BULK STORAGE TANK	$34,000	$ 64,000
MISCELLANEOUS EQUIPMENT	28,528	28,528
FOUNDATION AND DIKE	6,899	7,897
SHELTER	8,500	10,000
FENCE	1,274	1,434
TOTAL	$79,201	$111,859

In a more recent BAC study for a facility to fuel a 150-vehicle fleet in New Zealand, it was estimated that the LNG storage provisions would cost about $72,000 and the dispensing equipment would cost about $38,000, for an equipment cost of $110,000. Other site costs were not included. The bulk storage tank would have a capacity in the range of 6000 to 15,000 gallons (Ref. 2-21).

Only one LNG station, that of the Atlanta Gas Light Company, is known to be presently serving a vehicle fleet in the United States, but several others may have been activiated in recent months to service experimental LNG systems manufactured by BAC.

2.4.3 Methanol Fueling Stations

There are no known domestic stations now dispensing neat methanol fuel, except those set up to support the methanol vehicle fleet evaluations in California. However, methanol differs from the gasoline and diesel fuel currently available nationwide primarily in its much lower energy content per unit volume and its greater corrosiveness and affinity for atmospheric moisture. At the expense of new storage tanks (if necessary), dispensing equipment modifications, and greater fuel transportation and distribution costs per unit energy, methanol could be made available at conventional public stations. One source estimates a methanol station cost of $30,000 to $60,000 if all new tanks and dispensing equipment are used (Ref. 2-58). For retrofit conversions of existing stations, which do not require a new storage tank, station costs should be considerably less (Ref. 2-30).

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3. VEHICLE OPERATION

This section discusses the operating characteristics of highway vehicles using natural gas (NG) and methanol as fuels. Both compressed natural gas (CNG) and liquefied natural gas (LNG) are considered. Methanol is included because it can be derived from NG or alternative resources and because it is a liquid fuel at normal ambient conditions.

Subsection 3.1 addresses the general advantages and disadvantages of NG use in spark-ignition (SI) and diesel or compression-ignition (CI) engines, first based on theoretical considerations and then based on laboratory engine experiments. Subsection 3.2 examines available performance, fuel economy, and exhaust emissions test data from fleet and experimental vehicles operated with NG. Comparisons are made with baseline gasoline configurations whenever possible. Subsection 3.3 summarizes general operational experience with NG vehicles, with emphasis on the advantages and disadvantages as perceived by fleet operators. In Subsection 3.4, methanol fuel is discussed, with the approach paralleling that taken for NG.

3.1 NATURAL GAS ADVANTAGES AND DISADVANTAGES

While NG has been used as a vehicle fuel for many years in Europe, it created little interest in the United States until the late 1960s. At that time, alleviation of air pollution was viewed as the key advantage of NG-fueled vehicles. Tight gasoline supplies during the 1973 oil embargo, soaring gasoline costs in the late 1970s, and increased availability of NG in present markets have triggered new interest in this fuel as an alternative to gasoline.

Fuel economy, performance, and emissions of NG-fueled SI engines all depend heavily on the degree to which the engine calibration and hardware configuration have been optimized to take advantage of the favorable characteristics of this fuel compared with gasoline. In addition, the proper basis for comparison is between vehicle configurations with equal

performance, driving range, and emissions. Most available vehicle data are not based on comparable, fully optimized systems, and so a conclusive assessment of the ultimate potential of NG is not possible at this time. This subsection, therefore, discusses the effect of NG fuel on vehicle operation on the basis of theoretical considerations and laboratory test data.

3.1.1 Theoretical Considerations

Table 3-1 lists the principal advantages and disadvantages of NG as a motor fuel, based partly on the fuel properties summarized in Table 3-2. The biggest plus is its high octane number, with a research octane

Table 3-1. Advantages and Disadvantages of Natural Gas Compared with Gasoline

ADVANTAGES	REMARKS
HIGH OCTANE NUMBER	RESEARCH OCTANE NUMBER OF UP TO 130; ALLOWS INCREASED COMPRESSION RATIO.
BROAD FLAMMABILITY LIMITS	ALLOWS OPERATION AT MUCH LEANER MIXTURES.
GASEOUS STATE	DECREASES THROTTLING LOSSES AT PART LOAD. LEADS TO BETTER CYLINDER-TO-CYLINDER FUEL DISTRIBUTION.
SIMPLE CHEMISTRY	LEADS TO LOWER HYDROCARBON EMISSIONS, LOWER SOOT AND DEPOSITS. HC EMISSIONS PRIMARILY NONREACTIVE METHANE.
DISADVANTAGES	**REMARKS**
GASEOUS STATE	TENDS TO DECREASE PEAK POWER OUTPUT -- LARGER ENGINE NEEDED TO MAINTAIN EQUAL VEHICLE PERFORMANCE. LEADS TO IN-VEHICLE STORAGE DIFFICULTIES.
LOW FLAME SPEED	TENDS TO DECREASE EFFICIENCY AND INCREASE OXIDES OF NITROGEN EMISSIONS.
VERY LOW CETANE NUMBER	CETANE NUMBER NEAR ZERO. NOT SUITABLE AS A PRIMARY FUEL FOR UNMODIFIED CONVENTIONAL DIESEL ENGINES.

Table 3-2. Thermochemical Properties of Fuels

PROPERTY	GASOLINE	NO. 2 DIESEL	METHANE	NATURAL GAS	METHANOL
HIGHER HEATING VALUE					
MASS BASIS, 10^3 BTU/LB	20.26	19.60	23.88	20.76-23.00	9.77
VOLUME BASIS, 10^3 BTU/GAL	123.59	138.80			64.87
LOWER HEATING VALUE					
MASS BASIS, 10^3 BTU/LB	18.90	18.40	21.52	18.67-20.80	8.57
VOLUME BASIS, 10^3 BTU/GAL	115.80	130.30			56.90
OCTANE RATING					
RESEARCH	91-95	15-35	≈130	≤130	110
MOTOR	83-87	10-30	125-130	≤125	92-94
CETANE RATING	16-19	45-55	0	0	0
STOICHIOMETRIC A/F RATIO	14.9	14.5	17.3	17.3	6.5
FLAME TEMPERATURE IN AIR, °F	3986	NA	3410	3450	3570
HEAT OF VAPORIZATION, BTU/LB	130-150	70-155	219	219	506
MAXIMUM BURNING VELOCITY, CM/SEC	33-47	33-47	39	23-36	44
MINIMUM AUTOIGNITION TEMPERATURE, °F	430-500	490	1000	≤1000	725

number (RON) of approximately 130. In principle, the high RON allows the engine to operate at high compression ratios, with accompanying efficiency and performance benefits. In addition, the NG's broad flammability limits allow smooth operation at very lean air-fuel ratios, which benefits thermal efficiency. The gaseous nature of the fuel also permits extension of the lean combustion limit by improving air-fuel mixing and distribution. Furthermore, it reduces engine pumping losses by displacing air, thereby reducing the amount of throttling required at any given power level. The simple chemistry of methane, the predominant component of NG, is also beneficial since it leads to lower soot formation and engine deposits, with much of the hydrocarbon (HC) emissions consisting of non-reactive methane. This is particularly encouraging in view of the Environmental Protection Agency (EPA) Notice of Proposed Rulemaking for amending vehicle emission standards to permit compliance with a non-methane hydrocarbon standard (46-FR-62366; December 23, 1981).

The primary disadvantage of NG arises from its gaseous nature, which results in a significant reduction in wide-open-throttle (WOT) engine power at all engine speeds. The gaseous fuel displaces air which would otherwise be inducted with partially liquid fuel and would result in higher power output per piston stroke. Lean operation further degrades power by limiting fuel input, unless WOT enrichment is employed. To main-

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tain vehicle performance, a larger engine is therefore needed with NG, which tends to degrade fuel economy because of increased frictional losses. The lower flame speed of NG tends to further decrease power and fuel economy by increasing the burning duration, although some of this loss can be recovered by spark timing changes, at the expense of higher HC and oxides of nitrogen (NO_x) emissions. Finally, the low cetane number of NG makes it unsuitable as the sole fuel for unmodified conventional diesel engines.

In conjunction with chemical or thermal ignition aids, however, NG may be used in diesels, although its use has been restricted to date to stationary, marine, and laboratory applications. No ignition aids in the form of fuel additives have been identified for NG. The NG is either injected directly into the cylinders or fumigated, i.e., inducted through the intake manifold. While these techniques may be feasible in principle, they add considerable complexity and cost and they have not been demonstrated to be practical for automotive retrofit applications, although some are in use in stationary engines.

Because of its simplicity and relative ease of implementation in diesel retrofit applications, NG fumigation in conjunction with pilot injection of diesel fuel is currently favored by most investigators. Compared with direct injection of diesel fuel, fumigation of NG should in theory increase air utilization, lower smoke emissions, and thereby permit an increase in smoke-limited engine power output in some applications. Relative to operation on diesel fuel only, NG fumigation generally results in a decrease in NO_x emissions at part load. Both carbon monoxide (CO) and HC emissions tend to increase at low load, unless the mass ratio of pilot fuel to NG is carefully regulated to prevent lean flameout in the bulk air-fuel mixture.

3.1.2 Laboratory Data

Available laboratory data, typically using single-cylinder engines, generally confirm the expected advantages and disadvantages of NG. For example, Figure 3-1 shows the high compression ratios attainable

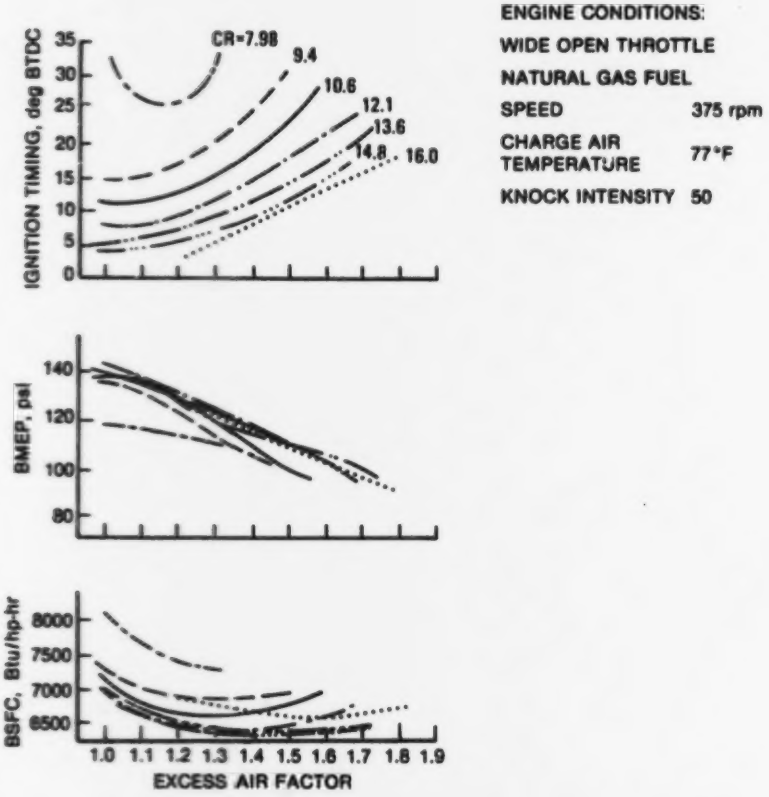

Figure 3-1. Natural Gas Performance at Higher Compression Ratios in a Single-Cylinder Engine (Ref. 3-1)

in a single-cylinder engine with NG and the resultant effect on power, fuel consumption, and MBT (minimum advance for best torque) spark timing over a range of air-fuel ratios (Ref. 3-1). The required spark advance decreases with increasing compression ratio, probably reflecting an increase in flame speed with increasing charge temperature. As expected, power and efficiency increase with compression ratio. Figure 3-2 shows the observed effect of compression ratio on passenger car fuel economy and octane requirements. At equal performance, vehicle fuel economy can be improved by about 15 to 20 percent by a compression ratio increase from 8 to 12. Extrapolation of the data in Figure 3-2 indicates that an RON of 104 to 106 is required to accommodate a compression ratio of 12. Since the RON of methane is approximately 130, a fuel economy effect of at least

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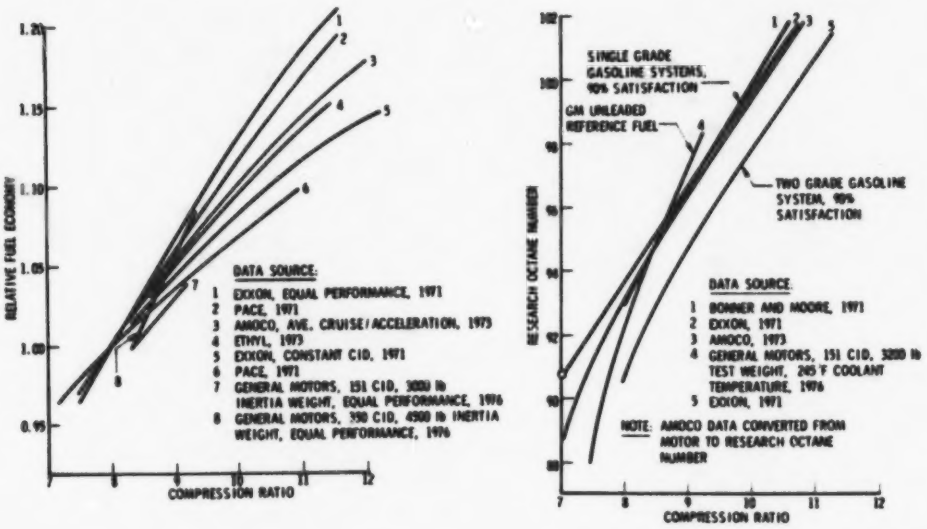
RELATIVE FUEL ECONOMY
COMPRESSION RATIO
DATA SOURCE:
1 EXXON, EQUAL PERFORMANCE, 1971
2 PACE, 1971
3 AMOCO, AVE. CRUISE/ACCELERATION, 1973
4 ETHYL, 1973
5 EXXON, CONSTANT CID, 1971
6 PACE, 1971
7 GENERAL MOTORS, 151 CID, 3000 lb INERTIA WEIGHT, EQUAL PERFORMANCE, 1976
8 GENERAL MOTORS, 350 CID, 4500 lb INERTIA WEIGHT, EQUAL PERFORMANCE, 1976
RESEARCH OCTANE NUMBER
SINGLE GRADE GASOLINE SYSTEMS, 90% SATISFACTION
GM UNLEADED REFERENCE FUEL
TWO GRADE GASOLINE SYSTEM, 90% SATISFACTION
DATA SOURCE
1 BONNER AND MOORE, 1971
2 EXXON, 1971
3 AMOCO, 1973
4 GENERAL MOTORS, 151 CID, 3200 lb TEST WEIGHT, 205°F COOLANT TEMPERATURE, 1976
5 EXXON, 1971
NOTE: AMOCO DATA CONVERTED FROM MOTOR TO RESEARCH OCTANE NUMBER
COMPRESSION RATIO

Figure 3-2. Relative Fuel Economy and Research Octane Number Requirement of Spark-Ignition Engines as a Function of Compression Ratio

this magnitude can probably be achieved with an SI engine designed for NG utilization, offset partially by other effects such as that due to lower flame speed. Emissions constraints, however, do not allow firm conclusions to be drawn without vehicle tests.

Figure 3-3 shows the extended flammability limits of NG compared with gasoline and illustrates the relative emissions. As can be seen, engine emissions with NG and gasoline have a qualitatively similar dependence on air-fuel ratio (Ref. 3-2). HC emissions are uniformly lower with NG than with gasoline. This may be partly due to the nondispersive infrared (NDIR) instrumentation used at the time, which is relatively insensitive to methane. NO_x emissions are lower for excess air factors up to about 1.2, probably because of lower combustion temperatures and slower combustion with NG. CO emissions are about the same for the two fuels. As shown in Table 3-3, HC emissions with NG are significantly less reactive, reflecting the preponderance of the nonreactive methane component of the fuel (Ref. 3-2). The effects of spark timing variations on fuel

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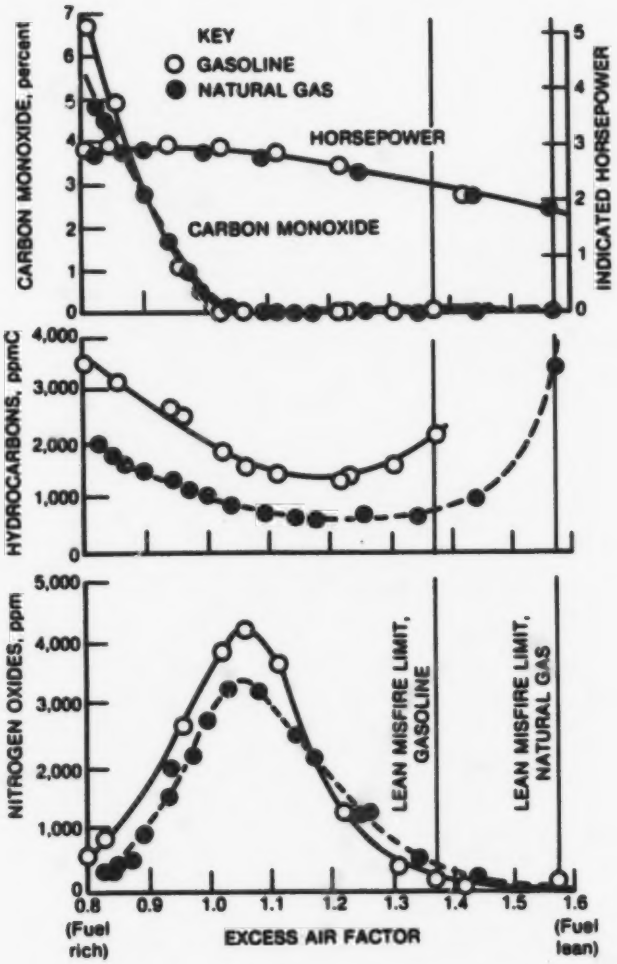

Figure 3-3. Emissions Characteristics of a Single-Cylinder Engine with Gasoline and Natural Gas (Ref. 3-2)

consumption and HC and NO_x emissions are illustrated in Figure 3-4 (Ref. 3-2). Similar to operation with gasoline, retarded spark timing results in lower HC and NO_x emissions, at the expense of an increase in fuel consumption. Advancing spark timing from 25 to 35 degrees before top dead center (BTDC) at an air-fuel ratio of 18 results in a 10 percent improvement in fuel consumption and a 230 percent increase in NO_x.

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Table 3-3. Exhaust Hydrocarbon Reactivities with Gasoline and Natural Gas Fuels (Ref. 3-2)

FUEL	EXCESS AIR FACTOR	REACTIVITY, G ETHYLENE/IMP-H
GASOLINE	1.0	0.72
	1.2	0.64
NATURAL GAS	1.0	0.16
	1.2	0.16

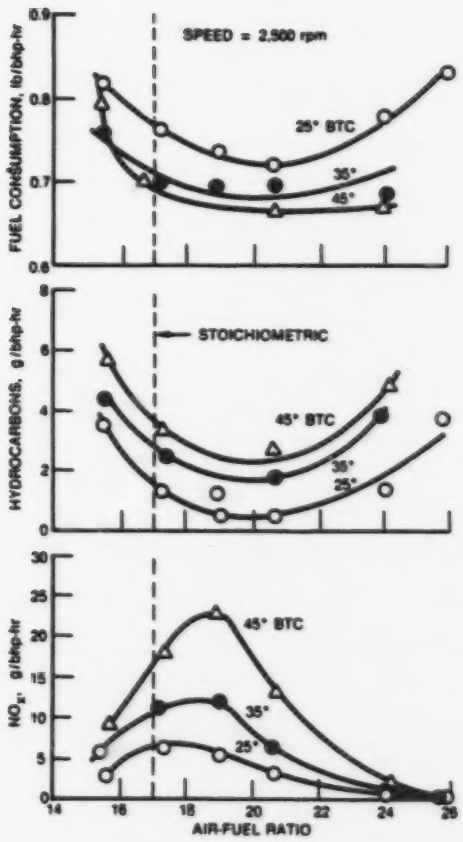

Figure 3-4. Effect of Ignition Timing on Fuel Consumption and Exhaust Emissions with Natural Gas (Ref. 3-2)

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Single-cylinder engine data at wide open throttle are presented in Figure 3-5 (Ref. 3-3). As shown, engine power output with NG is only 65 to 80 percent of that with isooctane for equivalence ratios between 0.8 and 1.2. (The equivalence ratio is the stoichiometric air-fuel ratio divided by the actual air-fuel ratio, and is the inverse of the excess air factor.) About a 9 percent power loss is attributable to the reduced volumetric efficiency with NG, adjusted for heating value differences. The remainder of the loss results from the lower flame speed and other factors. It should be noted that the high mechanical friction of the single-cylinder engine relative to a production engine exaggerates the relative power drop, and a lesser power decline would be expected in a vehicle application, as well as a higher thermal efficiency. For example, Table 3-4

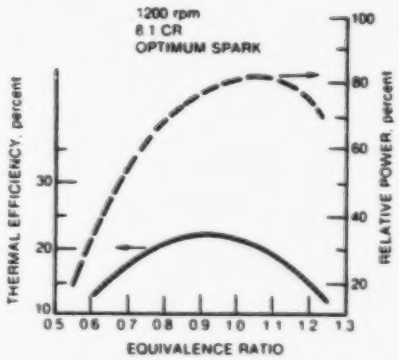

Figure 3-5. Effect of Equivalence Ratio on Thermal Efficiency and Relative Power in a Single-Cylinder Engine with CNG (Ref. 3-3)

Table 3-4. Emissions and Power with Natural Gas Relative to Gasoline (Ref. 3-4)

	Percent of Gasoline Value @ Spark Timing			
Parameter	0^0 BTDC	5^0 BTDC	10^0 BTDC	15^0 BTDC
HC	41	40	66	52
CO	32	21	15	32
Power	74	78	88	72

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shows the observed power loss for a CNG-fueled truck, at various initial spark timing settings, and the corresponding HC and CO emissions (Ref. 3-4). The vehicle is a 1978 Bedford J1 truck, operating at part throttle and 1500 to 2500 rpm engine speed. At the optimum spark timing, the power output with NG is 88 percent of that with gasoline.

There are only limited laboratory data on CI engines using NG. In general, it confirms the theoretically expected behavior. A discussion of the applicable experimental results is given in Volume III, Appendix B, of this report.

3.2 NATURAL GAS VEHICLE TEST DATA

This subsection summarizes available emissions, performance, and fuel economy test data from NG-fueled vehicles. Fleet data are summarized in Table 3-5, which is based on information acquired from operators of CNG and LNG fleets. Data from experimental CNG and LNG vehicles and engines are summarized in Table 3-6. A detailed discussion of these data can be found in Volume III, Appendix B, of this report.

Only three of the 13 fleet operators listed in Table 3-5 provided exhaust emission data from one or more of their CNG and baseline gasoline vehicles. These data indicate significant emission reductions with CNG, amounting to 45 to 84 percent for HC, 75 to 80 percent for CO, and 50 to 65 percent for NO_x. These reductions are attributed to two basic factors: (1) Unlike the gasoline vehicles, the CNG-fueled vehicles are operated very lean (about 25%), which is beneficial for emissions, and (2) the baseline vehicles use relatively rich air-fuel ratios, which result in high baseline emissions. All three HC measurements used NDIR instrumentation, which is relatively insensitive to methane.

Eight of the 13 fleet operators reported an increase in acceleration time or an engine power loss with NG, but only three of these users provided quantitative results. Engine power declined by an everage of 18 percent in one fleet, and average vehicle acceleration times increased by 20 to 47 percent, which is consistent with the observed power loss. Other users reported acceleration time increases of 32 and 47 percent.

Table 3-5. Summary of Natural Gas Vehicle Data - Fleet Operators

ORGANIZATION	VEHICLE MODEL YEAR	VEHICLE TYPE	OPTIMIZATION PARAMETER	PERCENTAGE CHANGE VS. GASOLINE HC	CO	NO_x	POWER	ACCEL. TIME	FUEL ECONOMY	ASSUMED BTU/GAL FACTOR	REFERENCE
CNG											
ARA, INC.	66 to 81	SERVICE	ECONOMY	-	-	-	DECR.	-	+30	100	9-4,4
BATTLE CREEK GAS CO.	73 to 81	SERVICE	ECONOMY	-	-	-	-	-	+37	100	9-7,8
EATON SCHOOL DISTRICT	69 to 79	BUSES	ECONOMY	-	-	-	DECR.	-	+11	124	9-8,10
GENERAL SERVICES ADMIN.	68 to 69	SERVICE	EMISSIONS	-84	-79	-65	-	+47	+11	120	9-11
CITY OF GREELEY	-	-	ECONOMY	-	-	-	-	-	+ 8	100	9-17
MICH. CONSOLIDATED GAS CO.	1969	SERVICE	EMISSIONS	-		-	-	+17	+ 2	125	9-19
SEDGWICK COUNTY	1980	POLICE	PERFORMANCE	-	-	-	DECR.	-	-17	100	9-24
SHAWNEE COUNTY	1980	POLICE	PERFORMANCE	-	-	-	DECR.	-	-40	100	9-25
SOUTHERN CALIF. GAS CO.	67 to 69	-	EMISSIONS	-50	-80	-62	-	-	+ 5	114	9-16,17
WASHINGTON GAS LIGHT CO.	-	SERVICE	ECONOMY	-	-	-	-	-	-	115	9-18
WELLINGTON GAS CO.	74 to 78	SERVICE	PERFORMANCE	+45	-75	-50	-10	+20	+13	100	9-19,20
YELLOW CAB CO.	-	TAXI	ECONOMY	-	-	-	-	-	-12	-	9-24
LNG											
ATLANTA GAS LIGHT CO.	74 to 81	SERVICE	ECONOMY	-	-	-	DECR.	-	+42	-	9-21

Table 3-6. Summary of Natural Gas Vehicle Data - Experimental Vehicles

ORGANIZATION	VEHICLE MODEL YEAR	VEHICLE TYPE	OPTIMIZATION PARAMETER	PERCENTAGE CHANGE VS. GASOLINE/DIESEL HC	CO	NO_x	POWER	ACCEL. TIME	FUEL ECONOMY	ASSUMED BTU/GAL FACTOR	REFERENCE
CNG											
DOE/BETC	1978	LDV	PERFORMANCE	+150	-12	+35	-	-	+1	106	9-22,29
DOE/BUREAU OF MINES	68 to 70	LDV	EMISSIONS	- 67	-67	-22	DECR.	DECR.	DECR.	-	9-2
DOE/EPA	79 to 80	LDV	EMISSIONS	+150	-79	-10	-27	+55	+1	130	9-26
DUAL FUEL SYSTEMS, INC.	77 to 81	LDV/PU	EMISSIONS	+540	-96	-46	-	-	+1	124	9-25,26
GENERAL MOTORS CORP.	1967	LDV	EMISSIONS	0	-83	-50	-15	-	-	-	9-16,27
LNG											
BEECH AIRCRAFT CORP.	1980	LDV	ECONOMY	SIM. TO GASOLINE				-	-	-	9-28,29,30
SHELL RESEARCH, LTD.	1970	LDV	ECONOMY	- 65	-80	+47	-24	-	+15	-	9-31
GAS DIESEL											
DOT/SwRI	DETROIT DIESEL		-	+1300	+900	-27	-10	-	-45	-	9-32

Comparative energy-equivalent fuel economy of the NG vehicles varies from a 30 percent loss to a 42 percent gain. Most of these vehicles are of the dual-fuel type with generally non-optimal spark timing and air-fuel mixture ratio calibrations. Frequently, questionable NG versus gasoline energy equivalency factors are used by fleet operators to establish gasoline-equivalent fuel economy, and this undoubtedly contributes to the spread in the reported fuel economy values. Other factors contributing to the large fuel economy variability are (1) differences in driving patterns, (2) variations in the degree of engine calibration optimization,

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and (3) comparison with some baseline gasoline vehicles in which fuel economy was compromised to meet emission standards. Service vehicles, which are typically operated in urban areas and frequently carry heavy loads, show the greatest improvement in fuel economy with NG. Many of these vehicles are calibrated with both fuel economy and performance in mind. Spark timing is often advanced relative to the baseline gasoline settings, and the air-fuel ratio is adjusted to values different from those specified by the CNG system manufacturer. The highest fuel economy losses were observed in police vehicles and taxicabs, in which engine power and vehicle acceleration capability are overriding concerns.

The information available from experimental NG-fueled vehicles is more complete. In general, these programs are conducted under more controlled conditions and allow quantification of fuels effects and vehicle operating differences. With two exceptions, recent-model vehicles were used in these tests. These vehicles have sophisticated emission control systems and improved engine components and calibrations relative to older vehicles. As a result, their baseline emissions are much lower than for early or pre-emission-control vehicles.

Although the experimental vehicle data are based on more controlled conditions, they show no conclusive efficiency benefit for NG operation. However, the vehicles tested do not reflect fully optimized configurations for NG. Tests performed during the course of this study without spark-timing modifications indicate approximately equal energy-equivalent fuel economy for NG and gasoline. In all cases, engine power was sacrificed for NG operation, and reported vehicle acceleration times increased by 20 to 55 percent. Since vehicle fuel economy generally increases with decreasing performance, the observed fuel economy changes overstate any beneficial effect attributable solely to NG use.

The use of NG generally provides further reductions in CO and NO_x as a direct result of leaner air-fuel mixture ratios. However, total HC emissions generally increase because catalytic converters are relatively ineffective in oxidizing methane, which is the principal HC species

emitted from NG-fueled engines. Emissions of the reactive non-methane hydrocarbons are generally lower with NG.

Similar to the fleet vehicles, the experimental NG vehicles show significant losses in engine power and vehicle acceleration. Energy-equivalent fuel economy of the CNG vehicles is essentially unchanged from the gasoline baseline values, while the LNG data vary. One LNG vehicle, converted similar to a CNG vehicle, showed a decrease in fuel economy. A second LNG vehicle, with advanced spark timing, increased compression ratio, and relaxed emissions constraints, showed a 13 percent fuel economy increase.

There is a lack of applicable CI vehicle data. However, the data available from one source are consistent with SI engine data in terms of emissions and engine power trends. In general, the NG-fueled diesel is poorly suited for vehicular applications, because of the requirement for ignition aids and the undesirable effects on power, emissions, and fuel economy at part load.

3.3 NATURAL GAS OPERATIONAL EXPERIENCE

Operational advantages and disadvantages of NG relative to gasoline are summarized in Table 3-7, as reported by organizations using CNG and LNG systems. The problems associated with CNG cylinder weight and engine power loss are expected to become less significant as technological advancements are made. However, packaging problems caused by cylinder volume may become relatively more severe as automobile downsizing continues. While a number of fleet operators have already converted their vehicles to NG, or are considering such conversions because of specific advantages, other fleet operators are concerned with the disadvantages and have rejected NG conversion of their vehicles at this time.

3.4 METHANOL

3.4.1 Advantages and Disadvantages

Some of the advantages and disadvantages of methanol as a motor fuel are summarized in Table 3-8, based partly on the fuel properties

Table 3-7. Operational Experience with Natural-Gas-Fueled Vehicles

ADVANTAGES	DISADVANTAGES
GREATLY REDUCED FUEL COSTS	GREATLY REDUCED DRIVING RANGE ON CNG
ENGINE LIFETIME EXTENDED	REDUCED ENGINE POWER REQUIRES LARGER ENGINES, HIGHER NUMERICAL FINAL DRIVE RATIO
EASY STARTING AND ENHANCED COLD-START DRIVEABILITY	CYLINDER HEIGHT AFFECTS STEERING AND MAY REQUIRE SUSPENSION CHANGES
SUBSTANTIALLY INCREASED SPARK PLUG LIFE	CYLINDERS OCCUPY NEEDED TRUNK SPACE
OIL CHANGE INTERVALS EXTENDED TO 25,000 MI	FREQUENT ENGINE/CNG SYSTEM TUNING FOR GOOD PERFORMANCE
REDUCED ENGINE MAINTENANCE BECAUSE OF NO CARBON BUILDUP	ENGINE KNOCKING IN GASOLINE MODE
REDUCED FUEL PILFERAGE	

Table 3-8. Advantages and Disadvantages of Methanol Compared with Gasoline

ADVANTAGES	REMARKS
HIGH OCTANE NUMBER	RESEARCH/MOTORING OCTANE NUMBER OF 110/90, PERMITS INCREASED COMPRESSION RATIO.
BROAD FLAMMABILITY LIMITS	PERMITS OPERATION AT LEANER MIXTURES.
HIGH LAMINAR FLAME SPEED	TENDS TO IMPROVE EFFICIENCY
HIGH HEAT OF VAPORIZATION	INCREASES VOLUMETRIC EFFICIENCY; DECREASES COMPRESSION WORK.
FAVORABLE CHEMICAL STOICHIOMETRY	LOWERS FLAME TEMPERATURE, TENDS TO REDUCE NO_x. MORE CYLINDER PRESSURE AND POWER BECAUSE MORE MOLES PRODUCT PER MOLES REACTANT. LOWER SOOT AND DEPOSITS BECAUSE ONLY ONE CARBON ATOM PER MOLECULE.
DISADVANTAGES	**REMARKS**
VERY LOW CETANE NUMBER	UNSUITABLE FOR DIESEL ENGINES WITHOUT MAJOR FUEL OR ENGINE MODIFICATION.
HIGH HEAT OF VAPORIZATION	LEADS TO MIXTURE PREPARATION AND CYLINDER-TO-CYLINDER FUEL DISTRIBUTION PROBLEMS IN UNMODIFIED SPARK-IGNITION ENGINES.
LOW VAPOR PRESSURE	CAUSES DIFFICULT COLD STARTING.
HIGH ALDEHYDE EMISSIONS	UNREGULATED POLLUTANT, UNPLEASANT ODOR. HEALTH EFFECTS AND ATMOSPHERIC REACTIVITY UNKNOWN.
LOW VOLUMETRIC ENERGY DENSITY	REQUIRES LARGER FUEL TANK (50-100%) FOR EQUAL VEHICLE RANGE.
HIGH POLARITY/ELECTRICAL CONDUCTIVITY	CAUSES MATERIALS COMPATABILITY AND CORROSION PROBLEMS.

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shown in Table 3-2. Methanol, like NG, has a high RON and broad flammability limits, with the associated potential for efficiency benefits from lean operation at high engine compression ratios. Unlike NG, it has a higher flame speed than gasoline, which also contributes to higher combustion efficiency. More important, it is a liquid fuel, with a relatively high heat of vaporization, which results in higher volumetric efficiencies than those achieved with gasoline because of the cooling effect of the vaporizing fuel on the incoming charge. Relative to gasoline, this allows higher power output per unit engine displacement.

However, unless offsetting design measures are taken, a problem arises with methanol as a result of its high heat of vaporization. At equal equivalence ratios, about seven times more heat is required for methanol vaporization than for gasoline. The increased heat requirement is partly caused by the higher mass flow rates required with methanol. Methanol has a stoichiometric air-fuel ratio of 6.45, less than half that of gasoline, and it has a heating value which is about half that of gasoline. Because methanol is more difficult to vaporize, mixture preparation and cylinder-to-cylinder distribution tend to be impaired, resulting in air-fuel ratio variations in the different cylinders. As a result, engine efficiency tends to decline, because there is no single spark timing that would be optimal for all cylinders, and because the overall lean limit is set by the leanest cylinder. Cold-start ability and driveability can also suffer, because of pooling of liquid fuel in the intake manifold.

Another potential problem with methanol is related to its low vapor pressure at normal ambient temperatures. Below about 50°F, the vapor pressure at typical engine cranking conditions is less than the amount necessary to produce an air-fuel mixture within the flammability limits for methanol. As a result, severe cold-start problems and poor driveability during engine warm up can occur, exacerbated by the high heat of vaporization which further depresses the temperature of the inlet charge. In addition, some of the materials conventionally used in automotive fuel systems are not compatible with methanol and must be replaced for acceptable long term functioning. For example, some plastics swell in

the presence of methanol, and the lead/tin plating which lines the inside of some vehicle fuel tanks tends to dissolve. Also, corrosion problems can occur as a result of the higher electrical conductivity of methanol, which encourages galvanic corrosion.

Emissions with methanol follow the same qualitative trends with air-fuel ratio, spark timing, and other engine parameters as with gasoline and NG. Quantitatively, the main difference is that NO_x emissions tend to be lower, primarily due to the lower flame temperatures with methanol. Another difference is the composition of the HC emissions. Methanol combustion tends to produce much higher aldehyde emission levels than gasoline, even though total hydrocarbon emissions are equivalent. Despite the effectiveness of current catalysts in oxidizing aldehydes once the catalyst warms up, cold-start emissions may present a problem. Although aldehyde emissions are presently unregulated, odor and atmospheric reactivity issues might arise with increased aldehyde emissions which would, in all likelihood, trigger new regulations.

To take full advantage of the properties of methanol, a number of engine calibration and hardware modifications must be made. The most important is an increase in engine compression ratio, to take advantage of the higher RON of methanol. The faster flame speed allows less spark advance, and the overall mixture can be made leaner for most operating conditions because of methanol's broad flammability limits. Optimized valve timing and EGR flow rates also help to improve fuel economy. However, realization of these potential benefits is contingent upon good mixture preparation and fuel distribution. This requires an increase in exhaust flow rate to the intake manifold hot spot, an increase in engine coolant flow rate through the manifold, or some other mixture heating provision. Cold-start capability requires more extensive provisions, such as fuel additives, electric heating, or a separate start-up fuel.

The feasibility of methanol as a practical diesel fuel has not been adequately established. Thermal or chemical ignition aids are required for engine operation. Glow plugs, spark assistance, pilot injec-

tion, fumigation, and chemical additives are all being considered, but all represent added cost and complexity to the base diesel engine. Compared with an optimized high-compression-ratio SI methanol engine, the traditional efficiency advantage of the diesel engine is greatly diminished, and the cost-effectiveness of methanol for this application may be questionable on an original equipment basis.

Laboratory data on methanol use in diesels are discussed in more detail in Volume III, Appendix B. As was the case with NG, fumigation is favored for retrofit applications. Methanol fumigation gives results similar to NG fumigation. The major difference is that methanol is a liquid fuel with a high heat of vaporization, which leads to higher volumetric efficiency, higher thermal efficiency because of reduced compression work, and higher peak power output for both of these reasons. NO_x emissions tend to be lower because of lower combustion temperatures. The higher flame speed of methanol further contributes to improved efficiency. Cold start is less of a problem than it is in SI engines, since warmup can take place using the pilot fuel only. Similar behavior is expected when the methanol is injected into the manifold rather than carbureted.

3.4.2 Vehicle Test Data

A number of experimental programs are presently under way to identify the characteristics of methanol-fueled vehicles and to evaluate methods of overcoming the fuel's known shortcomings. Since methanol does not represent the main thrust of this report, an exhaustive search for fleet data was not performed. Instead, readily available information on representative activity was reviewed, and is discussed in more detail in Volume III, Appendix B.

The basic technical feasibility of methanol as a fuel for SI engines is well established. With some modifications, primarily to fuel system materials and carburetor jets, existing automobiles may in most cases be converted to methanol operation. Satisfactory cold-start characteristics have been demonstrated with various techniques, ranging from fuel additives to add-on hardware. Similar to the situation with NG, fuel

economy with methanol depends on the degree to which the engine is modified to take advantage of the high RON, broad flammability limits, high flame speed, and other favorable characteristics of this fuel. Table 3-9 summarizes some of the methanol vehicle data discussed in Appendix B. With carburetor and spark timing changes only, both increases and decreases in energy economy have been observed. Emissions changes are also inconsistent. More recent data, with increased engine compression ratios and better engine calibrations, have shown that consistent improvements in both emissions and energy economy are attainable, and that NO_x emissions can be traded for fuel economy. On this basis, it appears that gains of 15 to 30 percent can be achieved with optimized methanol vehicles, depending on emissions constraints.

Table 3-9. Summary of Selected Methanol Vehicle Data

				PERCENTAGE CHANGE IN:						
ORGANIZATION	VEHICLE	MODEL YEAR	ENGINE	HC	CO	NO_x	ALDEHYDES	ACCEL. TIME	CITY FUEL ECONOMY	REFERENCE
BETC	DODGE	1976	5.2L-V8	-20	-33	-70	+575	-	+8	3-33
U. OF MISSOURI	CIVIC	1975	1.5L-I4	INCR.	INCR.	-70	-	-	+6	3-34
U. OF SANTA CLARA	PINTO	1978	2.3L-I4	-47	+4	-31	+191	-	-2	3-35
			2.3L-I4 TURBO	+87	+42	-71	-	-	+14	3-36
STATE OF CALIF.	ESCORT	1980	1.6L-I4	-50	-37	-73	-	-	-3	3-37,
			@ 11.4 CR	-	-	-25	-	-	+12	3-38
				-	-	+40	-	-	+29	
VOLKSWAGEN	RABBIT	1980	1.6L-I4 @ 12.5 CR	-78(1)	-60(1)	-55(1)	-	-	+15(2)	3-39, 3-40

(1) ECE DRIVING CYCLE.
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4. RESOURCE ENERGY UTILIZATION

One basis for comparing natural gas (NG) and methanol to petroleum-derived gasoline and diesel fuel is the overall resource energy utilization efficiency. This figure of merit takes into account logistic chain energy expenditures from raw material extraction to fuel dispensing, as well as the vehicle fuel utilization efficiency. Resource utilization efficiency is not the only fuel evaluation criterion, however, since economic, environmental, and availability considerations are also important.

Resource utilization efficiency is the product of the logistic chain efficiency and the vehicle efficiency. The logistic chain efficiency is the product of the efficiencies for extraction, preparation, chemical conversion, product cleanup, storage, transportation, distribution, compression or liquefaction, and dispensing. It is essentially independent of the end use. Conversely, vehicle energy efficiency is impacted by the engine efficiency characteristics with each fuel, by vehicle weight, and by vehicle mission constraints regarding performance, driving range, and emissions.

The efficiencies discussed here are based on total energy input and output, regardless of the form of the energy. It should be noted that this energy analysis is not all-inclusive. For example, consideration of the energy consumed in the manufacture of equipment, supplies, and facilities for fuel production was beyond the scope of this study. Similarly, the energy for the manufacture of vehicle conversion kits and fueling station equipment was excluded, and not all possible fuel/resource combinations were addressed.

4.1 LOGISTIC CHAIN EFFICIENCY

Efficiencies for each major step in the fuel production process are listed in Tables 4-1 through 4-5. The first four tables cover compressed natural gas (CNG), liquefied natural gas (LNG), and methanol

Table 4-1. Logistic Chain Efficiency from Resource to Vehicle
Input -- Energy Resource: Natural Gas

PROCESS	PROCESS EFFICIENCY		
	CNG	LNG	METHANOL
EXTRACTION/GATHERING	0.964	0.964	0.964
PREPARATION/PROCESSING	0.968	0.968	0.968
CONVERSION	NA	NA	0.64
TRANSPORT	0.95	0.95	0.98
PRODUCT CLEANUP / LIQUEFACTION	NA	0.86	NA
STORAGE	0.996	0.997	1.00
DISTRIBUTION	0.993	0.99	0.98
COMPRESSION	0.89-0.98	NA	NA
DISPENSING	1.00	0.98	0.99
TOTAL	0.78-0.86	0.74	0.57

Table 4-2 Logistic Chain Efficiency from Resource to Vehicle
Input -- Energy Resource: Coal

PROCESS	PROCESS EFFICIENCY		
	CNG	LNG	METHANOL
SURFACE MINING	0.986	0.986	0.986
PREPARATION/PROCESSING	0.95	0.95	0.95
CONVERSION	0.65	0.65	0.62
TRANSPORT	0.95	0.95	0.98
PRODUCT CLEANUP / LIQUEFACTION	NA	0.86	NA
STORAGE	0.996	0.997	1.00
DISTRIBUTION	0.993	0.99	0.98
COMPRESSION	0.89-0.98	NA	NA
DISPENSING	1.00	0.98	0.99
TOTAL	0.51-0.56	0.48	0.55

Table 4-3. Logistic Chain Efficiency from Resource to Vehicle Input -- Energy Resource: Wood

PROCESS	PROCESS EFFICIENCY		
	CNG	LNG	METHANOL
HARVESTING	0.978	0.978	0.978
LOCAL TRANSPORT	0.979	0.979	0.979
CONVERSION	0.60	0.60	0.55
TRANSPORT	0.95	0.95	0.98
PRODUCT CLEANUP / LIQUEFACTION	NA	0.86	NA
STORAGE	0.996	0.997	1.00
DISTRIBUTION	0.993	0.99	0.98
COMPRESSION	0.89-0.98	NA	NA
DISPENSING	1.00	0.98	0.99
TOTAL	0.48-0.53	0.45	0.50

Table 4-4. Logistic Chain Efficiency from Resource to Vehicle Input -- Energy Resource: Municipal Solid Waste

PROCESS	PROCESS EFFICIENCY		
	CNG	LNG	METHANOL
COLLECTION	0.97	0.97	0.97
PREPARATION/PROCESSING / CONVERSION	0.50	0.50	0.40
PRODUCT CLEANUP / LIQUEFACTION	NA	0.86	NA
STORAGE	NA	0.997	1.00
DISTRIBUTION	0.993	0.99	0.98
COMPRESSION	0.89-0.98	NA	NA
DISPENSING	1.00	0.98	0.99
TOTAL	0.43-0.47	0.40	0.38

Table 4-5. Logistic Chain Efficiency from Resource to Vehicle Input -- Energy Resource: Petroleum

PROCESS	PROCESS EFFICIENCY	
	GASOLINE	DIESEL FUEL
EXTRACTION/RECOVERY	0.97	0.97
TRANSPORT (CRUDE)	0.975	0.975
PREPARATION CONVERSION/REFINING	0.93	0.95
STORAGE	1.00	1.00
TRANSPORT (PRODUCT)	0.975	0.975
DISTRIBUTION DISPENSING	0.98	0.98
TOTAL	0.84	0.86

fuels produced from NG, coal, wood, and municipal solid waste (MSW) resources in that order. Table 4-5 shows comparable efficiency data for gasoline and diesel fuel produced from petroleum. These data are discussed extensively in Volume III, Appendix C, and noted briefly here.

The most significant step for CNG is compression efficiency, which ranges from 0.89 to 0.98. These values were adopted based on published AGA data and personal discussions (Refs. 4-1 and 4-2). The lower efficiency reflects the low compressor inlet pressures (less than 5 psig) typical of medium-pressure distribution lines, with discharge pressures of 3000 to 3600 psig as required to fill 2400-psig vehicle tanks. The higher value is typical of a large installation with compressor intake from a nearby transmission line at pressures of 300 psig or above. In this case, it may be possible to use a gas booster, powered by the pressure differential between the transmission line and a large distribution line. Unfortunately, this is currently a rare situation applied by only a few gas utilities (Ref. 4-3). For electrically powered compressors used in most installations, resource usage was calculated based on an electrical generation and transmission efficiency of 34 percent.

Distribution and dispensing efficiencies for LNG and methanol are based on those for liquid hydrogen and gasoline, respectively, adjusted for differences in physical properties (Refs. 4-4 and 4-5). In all cases, these operations are very efficient. For CNG, cylinder filling was assumed to be leak-free. Transport efficiencies for the three fuels are based on a common distance of 1000 miles from the production plant to the fueling station. Gas transport is by pipeline, while rail shipment is assumed for methanol. It is also conceivable that LNG could be produced at the gas source and transported by rail at a somewhat higher efficiency and cost.

For petroleum-based gasoline and diesel fuel, the efficiencies listed in Table 4-5 were for the most part taken from Reference 4-5. Although various values are reported in the literature for some of the production steps, total logistic chain values do not differ widely. For example, the total efficiency used by the AGA is 0.85 for gasoline (Ref. 4-1), in good agreement with Table 4-5, although the individual step values vary, partially due to definitional differences.

Total logistic chain efficiencies are summarized in Table 4-6. Only CNG has a logistic chain efficiency approaching that of gasoline or diesel fuel. The logistic chain efficiency for LNG is about 12 percent lower than that of gasoline. Methanol and SNG efficiencies are substantially lower than those of petroleum-based fuels. Production of methanol from coal is about as efficient as producing it from NG, and about as efficient as production of compressed SNG from coal. These logistic chain efficiencies will be used in Subsection 4.3 for the calculation of resource utilization efficiency.

4.2 VEHICLE ENERGY EFFICIENCY

Experimental data and the reported experiences of operators of NG-powered fleets are reviewed in Section 3 and in Volume III, Appendix B. In this subsection, these results are used to analyze the effects of CNG, LNG, and methanol operation on vehicle fuel economy, performance, weight, and other characteristics. Vehicle fuel economy calculations are based on

Table 4-6. Logistic Chain Efficiency from Resource to Vehicle Input

FINISHED FUEL	LOGISTIC CHAIN EFFICIENCY FROM RESOURCE				
	PETROLEUM	NATURAL GAS	COAL	WOOD	MSW
GASOLINE	0.84	-	-	-	-
DIESEL FUEL	0.86	-	-	-	-
COMPRESSED NATURAL GAS	-	0.78-0.86	0.51-0.56	0.48-0.53	0.43-0.47
LIQUEFIED NATURAL GAS	-	0.74	0.48	0.45	0.40
METHANOL	-	0.57	0.55	0.50	0.38

a simplified model, in which influence coefficients are used to approximate the fuel economy effects of changes in weight, power, and thermal efficiency. The influence coefficients were derived from computer simulations. A similar approach was used to calculate changes in vehicle performance. More refined models would require the development of a comprehensive engine and vehicle data base. Although the weight and volume required for the alternative fuel systems are important practical concerns, the primary purpose here is to compare fuel consumption, and therefore onboard space and weight requirements are mentioned only briefly.

4.2.1 Vehicle Assumptions

Table 4-7 shows some of the characteristics of the four baseline vehicles selected for analysis. The light-duty spark-ignition (SI) and diesel vehicles differ only in their powertrains, and have performance and fuel economy consistent with real subcompact vehicles. The light-duty vehicles are assumed to operate in an urban driving mode characterized by low-speed and part-load operation. The heavy-duty SI and diesel vehicles share a common Class 8 body, and operate primarily in a highway driving mode, where operation at high load predominates.

The weights shown for each of the four vehicles in Table 4-7 exclude the weight of the fuel system, i.e., tank, fuel, mounting brackets, fuel lines, pressure regulators, mixers, etc. This allows direct comparison of the weight penalties associated with each vehicle-fuel system combination. The fuel economy, acceleration time, driving

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Table 4-7. Characteristics of Baseline Light- and Heavy-Duty Vehicles Used for Simulation Study

VEHICLE CHARACTERISTIC	LIGHT-DUTY		HEAVY-DUTY	
	SPARK-IGNITION	DIESEL	SPARK-IGNITION	DIESEL
OPERATING CHARACTERISTICS				
FUEL ECONOMY, MPG	28	42	3.9	4.6
0-60 MPH ACCELERATION, SEC	17.6	25.3	100(1)	144(1)
DRIVING RANGE, MI	350	350	500	500
VEHICLE ASSUMPTIONS				
INERTIA WEIGHT,(2) LB	2293	2293	72,000	72,000
AVAILABLE ENGINE POWER, BHP	69	51.8	400	300
FRONTAL AREA, FT^2	18.2	18.2	100	100
DRAG COEFFICIENT	0.44	0.44	1.0	1.0
ROLLING RESISTANCE COEFFICIENT	0.012	0.012	0.010	0.010
DRIVING CYCLE	URBAN	URBAN	HWY	HWY

(1) PERCENTAGE OF SI VEHICLE ACCELERATION TIME.
(2) EXCLUDING FUEL SYSTEM.

range, and engine power shown are those for operation on the baseline gasoline or diesel fuel. Zero to 60 mph acceleration times for Class 8 trucks are not normally cited, and these are shown only as relative quantities.

Six comparisons were made for each of the four baseline vehicles: (1) baseline operation on gasoline or diesel fuel, (2) dual-fuel operation on CNG, (3) dual-fuel operation on LNG, (4) single-fuel operation on CNG, (5) single-fuel operation on LNG, and (6) single-fuel operation on methanol. The dual-fuel vehicles reflect typical retrofits of existing vehicles, which retain the baseline fuel system and add the alternative fuel system. The diesel retrofits are based on the assumption that fumigation with pilot injection becomes a practical technique for vehicles, allowing much of the conversion hardware to be the same as with the SI vehicles. The single-fuel conversions reflect vehicles that are dedicated to, and optimized for, operation on the alternative fuels.

Table 4-8 summarizes the relative thermal efficiency and power assumed for the five types of alternative-fueled vehicles. The assumptions are based on the results of fleet user experiences and laboratory

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Table 4-8. Relative Thermal Efficiency and Power of Retrofit Dual-Fuel and Single-Fuel Vehicles

VEHICLE CHARACTERISTICS	DUAL-FUEL CNG OR LNG	SINGLE-FUEL CNG OR LNG	SINGLE-FUEL METHANOL
RELATIVE THERMAL EFFICIENCY			
LIGHT-DUTY			
SPARK-IGNITION	1.00	1.23	1.20
DIESEL	0.90	0.90	0.90
HEAVY-DUTY			
SPARK-IGNITION	1.00	1.23	1.20
DIESEL	1.05	1.00	1.00
RELATIVE ENGINE POWER			
LIGHT-DUTY			
SPARK-IGNITION	0.75	1.12	1.20
DIESEL	0.90	0.90	1.00
HEAVY-DUTY			
SPARK-IGNITION	0.75	1.12	1.20
DIESEL	1.10	1.10	1.10

experiments discussed in Section 3 and Volume III, Appendix B. CNG and LNG are assumed to yield equivalent results, since the two fuels are similar in composition and LNG systems generally vaporize the fuel before use.

The dual-fuel SI retrofits assume equivalent thermal efficiency and a 25 percent power loss while operating on NG, regardless of duty cycle, in accordance with the results of DOE dynamometer tests outlined in Volume III, Appendix B. These assumptions correspond to typical NG conversions, in which initial spark timing is not advanced, a lean air-fuel ratio is used, and no provision is made for wide-open-throttle (WOT) mixture enrichment.

The single-fuel SI conversions reflect a compression ratio (CR) of 14 for the NG vehicles, a CR of 11 for the methanol vehicles, optimum spark timing, and near-stoichiometric operation at WOT. The resulting power and thermal efficiencies for these vehicles are estimated to be 12 to 23 percent higher than baseline.

In the case of the alternative-fuel diesels, the operating cycle also affects the average thermal efficiency. While thermal efficiency and available power are often increased at high load, both are lower at part load, according to laboratory tests of single and multi-cylinder engines. The assumptions in Table 4-8 are estimates of the average thermal efficiency and available power under part-load and full-load conditions that approximate the urban and highway driving modes.

The dual-fuel diesel efficiency and power assumptions are based on the results of NG fumigation experiments by Italian investigators, in which thermal efficiency and power were increased by 5 percent and 10 percent, respectively, at full load and decreased by 10 percent at part load compared to operation without fumigation (Ref. 4-7). The alternative fuel substitutes for 42.5 percent of total fuel energy over the part-load urban cycle and for 76.5 percent of total fuel energy over the highway cycle, in accordance with the Italian experience, which indicates a maximum NG substitution of 85 percent at full load.

The single-fuel diesels assume exclusive alternative fuel operation, using thermal ignition aids or cetane improvers. Thermal efficiency is estimated to be unchanged at full load and decreased by 10 percent at part load, relative to operation on diesel fuel. The available power is increased by 10 percent at full load and is equal or decreased by 10 percent at part load. These assumptions are judgmental estimates based upon the results of NG and methanol-fueled engine tests.

The irfluence of inertia weight changes on fuel consumption was estimated from tractive energy requirements over the operating cycle, as described by General Motors (Ref. 4-8). The influence coefficient, which is the percentage change in fuel consumption for each percent change in weight, is 0.752 for the light-duty vehicles and 0.605 for the heavy-duty vehicles. Fuel tank ullage was ignored, as were secondary weight changes, such as adding a stiffer suspension or chassis reinforcement to accommodate fuel system weight increases.

4.2.2 Light-Duty SI Vehicles

Table 4-9 details the capacity and weight characteristics of the light-duty SI-vehicle fuel systems. The gasoline system requires a 12.5 gallon tank with a dry weight (including mounting straps, fuel lines, float gauge, etc.) of 25 lb. For the purpose of calculating the average fuel consumption weight penalty, fuel weights for all vehicles were based on half a tank, except the gasoline weights for the dual-fuel SI vehicles. For these vehicles a nominal quarter tank of gasoline was assumed, since the driver presumably uses gasoline only if the NG supply is exhausted.

Table 4-9. Fuel System Parameters for Simulated Light-Duty Spark-Ignition Vehicles

PARAMETER	GASOLINE	DUAL-FUEL		SINGLE-FUEL		
		CNG	LNG	CNG	LNG	METHANOL
GASOLINE SYSTEM						
TANK CAPACITY, GAL	12.5	12.5	12.5	0	0	0
TANK WEIGHT(1), LB	25	25	25	0	0	0
FUEL WEIGHT(2), LB	38	19	19	0	0	0
ALTERNATIVE FUEL SYSTEM						
TANK CAPACITY, GAL (SCF)	0	(477)	18	(1525)	15.6	21.5
TANK WEIGHT(1), LB	0	204	117	650	100	35
FUEL WEIGHT(2), LB	0	11	32	34	28	71
TOTAL FUEL SYSTEM WEIGHT, LB	63	259	194	684	128	106
URBAN CYCLE ENERGY PENALTY FOR FUEL SYSTEM WT	1.021	1.085	1.064	1.224	1.042	1.035

(1) TANK WEIGHTS INCLUDE STEEL TANK, FUEL LINES, MOUNTING HARDWARE, REGULATOR, AND MIXER/VAPORIZER IF USED.
(2) GASOLINE WEIGHTS FOR DUAL-FUEL SYSTEMS ARE BASED UPON 1/4 TANK OF FUEL. ALTERNATIVE FUEL WEIGHTS ARE BASED UPON 1/2 TANK OF FUEL.

The dual-fuel CNG systems are sized to provide a minimum of 100 miles of CNG operation. The light-duty SI system requires 477 standard cubic feet (scf) of CNG contained in one 195 scf tank and one 282 scf tank that weigh a total of 204 lb, including mounting brackets, fuel lines, mixer assembly, and pressure regulator. All CNG tank weights and

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capacities are based on the characteristics of standard DOT 3AA 2400 psig tanks. The dual-fuel LNG system is sized for an 18 gallon LNG tank, similar to those described by Beech and Atlanta Gas Light Company (Refs 4-9 and 4-10). The fuel systems of the three single-fuel vehicles are all sized to provide a 350 mile driving range. The resulting fuel system weights range from 63 lb for the gasoline vehicle to 684 lb for the single-fuel CNG vehicle. These weight increases incur fuel consumption penalties of 2 percent to 22 percent, respectively.

The top half of Table 4-10 illustrates the complete characteristics of the light-duty SI vehicles. The gasoline vehicle has a fuel economy of 28 mpg, accelerates from 0 to 60 mph in 17.6 seconds and has a range of 350 miles. The energy-equivalent fuel economy of the dual-fuel CNG vehicle is 26.3 mpg_e. It accelerates more slowly because it is heavier and has less power, but driving range is greater. The dual-fuel LNG vehicle has higher fuel economy than the CNG car and a much greater driving range.

The single-fuel NG and methanol engines enjoy energy-equivalent fuel economies higher than that of the baseline gasoline engine. However, the heavy fuel system of the single-fuel CNG vehicle degrades its fuel economy and performance relative to the LNG vehicle. The CNG system requires the equivalent of about four 325 scf tanks plus one 195 scf tank, occupying about 12 to 13 cubic feet. For comparison, the 12.5 gallon gasoline tank occupies about 1.8 cubic feet. The LNG system is much lighter and more compact than the CNG system. The LNG fuel system weighs 128 lb and its 15.6 gallons of fuel will require about 3 cubic feet when the thickness of both the tank wall and the insulation are included. In addition to its relative compactness, the optimized engine-fuel combination boosts the available power to 77 bhp and the urban fuel economy to 33.7 mpg_e. The methanol vehicle is very similar, although it has a little more power. At 106 lb, its fuel system is slightly lighter than that of the LNG vehicle and, although fuel volume is greater, occupies about the same space, 3 cubic feet. Fuel economy is 33.1 mpg_e, which is slightly less than that of the LNG vehicle.

Table 4-10. Simulation Results for Light-Duty Spark-Ignition Alternative-Fuel Vehicles

VEHICLE CHARACTERISTICS	GASOLINE BASELINE	DUAL-FUEL CNG	DUAL-FUEL LNG	SINGLE-FUEL CNG	SINGLE-FUEL LNG	SINGLE-FUEL METHANOL
RETROFIT CONVERSIONS						
OPERATING CHARACTERISTICS						
CITY FUEL ECONOMY, MPG_E	28.0	26.3	26.9	28.7	33.7	33.1
0-60 MPH ACCELERATION TIME, SEC	17.6	28.0	26.9	20.6	15.7	14.1
DRIVING RANGE, MI						
GASOLINE	350	329	336	0	0	0
ALTERNATIVE FUEL	0	100	323	350	350	350
TOTAL	350	429	659	350	350	350
CITY FUEL CONSUMPTION, BTU/MI						
LOWER HEATING VALUE	4136	4395	4309	4032	3432	3494
HIGHER HEATING VALUE	4433	4860	4782	4459	3809	3983
VEHICLE ASSUMPTIONS						
INERTIA WEIGHT, LB	2356	2552	2487	2977	2421	2399
AVAILABLE ENGINE POWER, BHP	69.0	51.8	51.8	77.3	77.3	82.8
GASOLINE TANK CAPACITY, GAL	12.5	12.5	12.5	0	0	0
ALTERNATIVE FUEL TANK CAPACITY, GAL (SCF)	0	(477)	18.0	(1525)	15.6	21.5
COMPARABLE VEHICLES						
OPERATING CHARACTERISTICS						
CITY FUEL ECONOMY, MPG_E	28.0	18.2	20.7	25.4	36.0	37.1
0-60 MPH ACCELERATION TIME, SEC	17.6	17.6	17.6	17.6	17.6	17.6
DRIVING RANGE, MI						
GASOLINE	350	250	0	0	0	0
ALTERNATIVE FUEL	0	100	350	350	350	350
TOTAL	350	350	350	350	350	350
CITY FUEL CONSUMPTION, BTU/MI						
LOWER HEATING VALUE	4136	6372	5583	4560	3126	3123
HIGHER HEATING VALUE	4433	7046	6196	5042	3570	3560
VEHICLE ASSUMPTIONS						
INERTIA WEIGHT, LB	2356	2857	2603	3104	2382	2345
AVAILABLE ENGINE POWER, BHP	69.0	83.7	76.2	90.9	69.8	68.7
GASOLINE TANK CAPACITY, GAL	12.5	13.8	0	0	0	0
ALTERNATIVE FUEL TANK CAPACITY, GAL (SCF)	0	(688)	25.4	(1724)	14.6	19.2

4.2.3 Comparable Light-Duty Vehicles

All six vehicles at the top of Table 4-10 were derived from a common baseline vehicle and have different ranges and acceleration capabilities. While this is useful for comparing the effects of fuel system changes on vehicle characteristics, the proper comparison basis is between

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vehicles with the same total range and acceleration capability, as shown at the bottom of Table 4-10. Only by equalizing these can the effect of the fuel alone be determined. In principle, the comparison should also be based on equal emissions, but that comparison can only be made by performing vehicle tests.

For the dual-fuel CNG vehicle, CNG range was held at 100 miles and both fuel systems were resized to yield a 350 mile total range. For the original dual-fuel LNG vehicle with a 659 mile range, the range on LNG is 323 miles. For the baseline-comparable vehicle with a range of only 350 miles, the gasoline system is discarded, since it is not needed for acceptable range. The optimized single-fuel vehicles are again designed for a range of 350 miles, at their new performance level.

Vehicle performance was adjusted by changing engine size, which also affects vehicle weight and fuel economy. The effect of engine power changes on engine weight was estimated by comparing the power to weight relationships of several commercially available engines. This resulted in a specific weight of 4 lb/bhp for SI engines and 7.5 lb/bhp for diesel engines operated on gasoline or diesel fuel, respectively. The influence of engine size changes on fuel economy was estimated from computer simulation results which are discussed in Volume III, Appendix B. Those results indicate a 0.53 percent fuel consumption increase for each percentage increase in engine power above baseline, with engine power based on operation on gasoline or diesel fuel.

On the basis of comparable vehicle performance and range, dual-fuel CNG fuel economy declines to 18.2 mpg_e from 26.3 mpg_e, and single-fuel CNG fuel economy, which was originally higher than for gasoline, decreases to 25.4 mpg_e from 28.7 mpg_e. In contrast, the other two single-fuel vehicles show improved fuel economy. At equal performance and range, the methanol vehicle has the highest fuel economy at 37.1 mpg_e, compared to 28 mpg for the baseline vehicle.

4.2.4 Light-Duty Diesel Vehicles

Table 4-11 summarizes the light-duty diesel results. All of the retrofit alternative-fuel vehicles cluster around 36 to 37 mpg_e, except the single-fuel CNG vehicle, which is the heaviest. All are slower and heavier than the baseline diesel. At equal performance and driving range, the methanol vehicle has the highest fuel economy among the alternative-fuel vehicles, while the single-fuel CNG vehicle has the lowest.

4.2.5 Heavy-Duty SI Vehicles

For the heavy-duty SI vehicles, the fuel system weight penalties shown in Table 4-12 are relatively small, except for the CNG cases. The retrofit dual-fuel CNG system requires 3249 scf of CNG, equivalent to nine tanks, each roughly 10 inches in diameter by 5 feet long and weighing 140 lbs. The retrofit single-fuel CNG system requires over four times as much CNG tankage as the dual-fuel system.

In contrast, the single-fuel LNG and methanol cases add little extra weight or space, and increase fuel economy and engine power. At equal performance and driving range, fuel consumption is 25 percent lower than for the baseline gasoline vehicle. Fuel tank volume is 20 to 70 gallons above baseline, and vehicle weights are within 200 lbs of each other.

4.2.6 Heavy-Duty Diesel Vehicles

Table 4-13 summarizes the heavy-duty diesel results. Here, it is the dual-fuel diesels which provide the largest gains in equivalent fuel economy, on both a retrofit and a comparable vehicle basis. The relative engine efficiencies are stronger influences on the truck fuel economies than for light-duty vehicles because the weight changes are smaller percentages of the total vehicle weights. The dual-fuel CNG systems require about 2200 scf, in six 372 scf tanks, in addition to their 90-100 gallon diesel fuel load. The dual-fuel LNG systems are smaller, with about a 130 gallon LNG requirement, and a 23 gallon diesel fuel requirement for the downsized engine.

Table 4-11. Simulation Results for Light-Duty Diesel Alternative-Fuel Vehicles

VEHICLE CHARACTERISTICS	DIESEL BASELINE	DUAL-FUEL		SINGLE-FUEL		
		CNG	LNG	CNG	LNG	METHANOL
RETROFIT CONVERSIONS						
OPERATING CHARACTERISTICS						
CITY FUEL ECONOMY, MPG_e	42.0	36.5	36.8	31.5	36.7	37.2
0-60 MPH ACCELERATION TIME, SEC	25.3	30.7	30.3	38.8	30.4	26.0
DRIVING RANGE, MI						
DIESEL FUEL (1)	350	274	117	0	0	0
ALTERNATIVE FUEL	0	100	350	350	350	350
TOTAL	350	374	467	350	350	350
CITY FUEL CONSUMPTION, BTU/MI						
LOWER HEATING VALUE	3103	3567	3544	4134	3549	3505
HIGHER HEATING VALUE	3305	3861	3843	4572	3939	3996
VEHICLE ASSUMPTIONS						
INERTIA WEIGHT, LB	2348	2455	2435	2967	2439	2400
AVAILABLE ENGINE POWER, BHP	51.8	46.6	46.6	46.6	46.6	51.8
DIESEL TANK CAPACITY, GAL	8.3	8.3	8.3	0	0	0
ALTERNATIVE FUEL TANK CAPACITY, GAL (SCF)	0	(164)	6.8	(1563)	16.1	21.6
COMPARABLE VEHICLES						
OPERATING CHARACTERISTICS						
CITY FUEL ECONOMY, MPG_e	42.0	32.0	32.9	19.6	32.5	36.5
0-60 MPH ACCELERATION TIME, SEC	25.3	25.3	25.3	25.3	25.3	25.3
DRIVING RANGE, MI						
DIESEL FUEL (1)	350	250	0	0	0	0
ALTERNATIVE FUEL	0	100	350	350	350	350
TOTAL	350	350	350	350	350	350
CITY FUEL CONSUMPTION, BTU/MI						
LOWER HEATING VALUE	3103	4067	3965	6650	4007	3568
HIGHER HEATING VALUE	3305	4402	4299	7353	4448	4067
VEHICLE ASSUMPTIONS						
INERTIA WEIGHT, LB	2348	2547	2499	3603	2519	2411
AVAILABLE ENGINE POWER, BHP	51.8	56.2	55.1	79.5	55.6	53.2
DIESEL TANK CAPACITY, GAL	8.3	8.8	6.1	0	0	0
ALTERNATIVE FUEL TANK CAPACITY, GAL (SCF)	0	(187)	7.7	(2514)	18.2	21.9

(1) NET OF DIESEL FUEL REQUIRED FOR ALTERNATIVE FUEL OPERATION.

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Table 4-12. Simulation Results for Heavy-Duty, Spark-Ignition Alternative-Fuel Vehicles

VEHICLE CHARACTERISTICS	GASOLINE BASELINE	DUAL-FUEL CNG	DUAL-FUEL LNG	SINGLE-FUEL CNG	SINGLE-FUEL LNG	SINGLE-FUEL METHANOL
RETROFIT CONVERSIONS						
OPERATING CHARACTERISTICS						
HIGHWAY FUEL ECONOMY, MPG_E	3.9	3.9	3.9	4.6	4.8	4.7
0-60 MPH ACCELERATION TIME, PERCENT OF BASELINE	100	148	147	94	86	79
DRIVING RANGE, MI						
GASOLINE	500	495	495	0	0	0
ALTERNATIVE FUEL	0	100	500	500	500	500
TOTAL	500	595	995	500	500	500
HWY FUEL CONSUMPTION, BTU/MI						
LOWER HEATING VALUE	29,700	30,000	30,000	25,100	24,200	24,900
HIGHER HEATING VALUE	31,800	33,200	33,200	27,800	26,800	28,300
VEHICLE ASSUMPTIONS						
INERTIA WEIGHT, LB	72,600	73,800	73,600	77,600	72,800	73,200
AVAILABLE ENGINE POWER, BHP	400	300	300	448	448	480
GASOLINE TANK CAPACITY, GAL	128	128	128	0	0	0
ALTERNATIVE FUEL TANK CAPACITY, GAL (SCF)	0	(3249)	195	(13,580)	157	219
COMPARABLE VEHICLES						
OPERATING CHARACTERISTICS						
HIGHWAY FUEL ECONOMY, MPG_E	3.9	3.2	3.2	4.7	5.1	5.1
0-60 MPH ACCELERATION TIME, PECENT OF BASELINE	100	100	100	100	100	100
DRIVING RANGE, MI						
GASOLINE	500	400	0	0	0	0
ALTERNATIVE FUEL	0	100	500	500	500	500
TOTAL	500	500	500	500	500	500
HWY FUEL CONSUMPTION, BTU/MI						
LOWER HEATING VALUE	29,700	36,200	35,700	24,500	22,800	22,700
HIGHER HEATING VALUE	31,800	40,000	39,600	27,000	25,300	25,800
VEHICLE ASSUMPTIONS						
INERTIA WEIGHT, LB	72,600	74,700	73,800	77,400	72,600	72,800
AVAILABLE ENGINE POWER, BHP	400	411	407	426	400	401
GASOLINE TANK CAPACITY, GAL	128	125	0	0	0	0
ALTERNATIVE FUEL TANK CAPACITY, GAL (SCF)	0	(3908)	232	(13,220)	148	199

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Table 4-13. Simulation Results for Heavy-Duty Diesel Alternative-Fuel Vehicles

VEHICLE CHARACTERISTICS	DIESEL BASELINE	DUAL-FUEL CNG	DUAL-FUEL LNG	SINGLE-FUEL CNG	SINGLE-FUEL LNG	SINGLE-FUEL METHANOL
RETROFIT CONVERSIONS						
OPERATING CHARACTERISTICS						
HIGHWAY FUEL ECONOMY, MPG_E	4.6	4.8	4.8	4.4	4.6	4.6
0-60 MPH ACCELERATION TIME, PERCENT OF BASELINE	144	129	129	141	128	129
DRIVING RANGE, MI						
DIESEL FUEL (1)	500	473	385	0	0	0
ALTERNATIVE FUEL	0	100	500	500	500	500
TOTAL	500	573	885	500	500	500
HWY FUEL CONSUMPTION, BTU/MI						
LOWER HEATING VALUE	28,300	27,200	27,100	29,800	28,400	28,500
HIGHER HEATING VALUE	30,200	29,800	29,800	32,900	31,600	32,500
VEHICLE ASSUMPTIONS						
INERTIA WEIGHT, LB	72,600	73,600	73,400	78,600	73,100	73,300
AVAILABLE ENGINE POWER, BHP	300	330	330	330	330	330
DIESEL TANK CAPACITY, GAL	109	109	109	0	0	0
ALTERNATIVE FUEL TANK CAPACITY, GAL (SCF)	0	(2249)	135	(16,070)	185	250
COMPARABLE VEHICLES						
OPERATING CHARACTERISTICS						
HIGHWAY FUEL ECONOMY, MPG_E	4.6	5.0	5.1	4.4	4.8	4.8
0-60 MPH ACCELERATION TIME, PERCENT OF BASELINE	144	144	144	144	144	144
DRIVING RANGE, MI						
DIESEL FUEL (1)	500	400	0	0	0	0
ALTERNATIVE FUEL	0	100	500	500	500	500
TOTAL	500	500	500	500	500	500
HWY FUEL CONSUMPTION, BTU/MI						
LOWER HEATING VALUE	28,300	26,000	25,800	29,500	27,100	27,200
HIGHER HEATING VALUE	30,200	28,500	28,300	32,600	30,100	31,000
VEHICLE ASSUMPTIONS						
INERTIA WEIGHT, LB	72,600	73,300	72,700	78,500	72,900	73,100
AVAILABLE ENGINE POWER, BHP	300	303	300	324	301	302
DIESEL TANK CAPACITY, GAL	109	88	23	0	0	0
ALTERNATIVE FUEL TANK, CAPACITY, GAL (SCF)	0	(2147)	128	(15,920)	176	239

(1) NET OF DIESEL FUEL REQUIRED FOR ALTERNATIVE FUEL OPERATION.

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4.2.7 Summary of Vehicle Results

Table 4-14 summarizes the energy consumption of each alternative-fuel vehicle relative to its baseline. The most efficient alternative-fuel SI vehicles on both a retrofit and a comparable basis are the single-fuel vehicles. For the diesels, the light-duty dual-fuel LNG and the single-fuel LNG and methanol vehicles are the most efficient, but for heavy-duty applications, dual-fuel vehicles are the most efficient. This is primarily a result of the different operating cycles assumed for these two vehicle classes.

4.3 OVERALL RESOURCE ENERGY CONSUMPTION

This subsection combines the supply chain efficiencies of the different fuel resources that were developed in Subsection 4.1 with the vehicle energy efficiencies developed in Subsection 4.2 to arrive at the overall resource energy efficiencies for different vehicle fuel combinations.

Tables 4-15 through 4-18 show the resource chain efficiencies, for retrofit configurations, based on the higher heating values of the fuels. In each case, the NG resource has the highest logistic chain efficiency for each finished fuel, and produces the lowest resource energy consumption. Table 4-19 summarizes the total resource energy consumptions from Tables 4-15 through 4-18 for the NG resource cases. For the light- and heavy-duty dual-fuel diesels, the petroleum-based diesel fuel pilot accounts for 66 and 23 percent of the energy consumption, respectively.

Comparing the entries in Table 4-14 to those in Table 4-19, several changes in energy use are apparent. The single-fuel methanol vehicles have some of the lowest vehicle fuel consumptions, but are the highest resource energy consumers due to the low methanol fuel production efficiency. CNG becomes a stronger competitor to LNG. Although CNG fuel economy is generally lower, it has a higher fuel production efficiency.

Table 4-14. Summary of Relative Vehicle Energy Consumption

	RELATIVE VEHICLE ENERGY CONSUMPTION (LHV)					
		DUAL-FUEL		SINGLE-FUEL		
	BASELINE	CNG	LNG	CNG	LNG	METHANOL
RETROFIT CONVERSIONS						
LIGHT-DUTY						
SPARK-IGNITION	100	106	104	98	83	84
DIESEL	100	115	114	133	114	113
HEAVY-DUTY						
SPARK-IGNITION	100	101	101	85	81	84
DIESEL	100	96	96	105	100	101
COMPARABLE VEHICLES						
LIGHT-DUTY						
SPARK-IGNITION	100	154	135	110	78	76
DIESEL	100	131	128	214	129	115
HEAVY-DUTY						
SPARK-IGNITION	100	122	120	82	77	76
DIESEL	100	92	91	104	96	96

With NG as the resource, only the single-fuel SI-engine NG systems consume less overall resource energy than the baseline. All diesel engine conversions result in higher resource energy consumption, except perhaps for the CNG dual-fuel heavy-duty diesel case. In all cases, the methanol systems require the highest amount of resource energy.

Table 4-15. Overall Resource Consumption for Light-Duty SI-Engine Vehicles

	RESOURCE CONSUMPTION(1), BTU/MI				
	DUAL-FUEL		SINGLE-FUEL		
RESOURCE	CNG	LNG	CNG	LNG	METHANOL
NATURAL GAS	5700-6200	6500	5200-5700	5100	7000
COAL	8700-9500	10,000	8000-8700	7900	7200
WOOD	9200-10,100	10,600	8400-9300	8500	8000
MSW	10,300-11,300	12,000	9500-10,400	9500	10,500

(1) BASED ON EPA URBAN DRIVING CYCLE AND HIGHER HEATING VALUE OF FUELS; BASELINE GASOLINE VEHICLE CONSUMES 5278 BTU/MI OF PETROLEUM.

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Table 4-16. Overall Resource Consumption for Light-Duty Diesel Vehicles

	RESOURCE CONSUMPTION[1], BTU/MI				
	DUAL-FUEL		SINGLE FUEL		
RESOURCE	CNG	LNG	CNG	LNG	METHANOL
NATURAL GAS					
NG	1949-2149	2259	5316-5861	5323	7010
PETROLEUM	2540	2524	-	-	-
TOTAL	4489-4689	4783	5316-5861	5323	7010
COAL					
COAL	2993-3287	3483	8164-8964	8206	7276
PETROLEUM	2540	2524	-	-	-
TOTAL	5534-5827	6007	8164-8964	8206	7276
WOOD					
WOOD	3163-3492	3715	8626-9524	8753	7992
PETROLEUM	2540	2524	-	-	-
TOTAL	5703-6032	6240	8626-9524	8753	7992
MSW					
MSW	3566-3898	4180	9227-10,630	9846	10,516
PETROLEUM	2540	2524	-	-	-
TOTAL	6107-6438	6704	9727-10,630	9846	10,516

(1) BASED ON EPA URBAN DRIVING CYCLE AND HIGHER HEATING VALUE OF FUELS; BASELINE DIESEL VEHICLE CONSUMES 3843 BTU OF PETROLEUM PER MI.

Table 4-17. Overall Resource Consumption for Heavy-Duty SI-Engine Vehicles

	RESOURCE CONSUMPTION[1], BTU/MI				
	DUAL-FUEL		SINGLE-FUEL		
RESOURCE	CNG	LNG	CNG	LNG	METHANOL
NATURAL GAS	38,500-42,500	44,900	32,300-35,600	36,300	49,700
COAL	59,200-65,000	69,200	49,600-54,500	55,900	51,500
WOOD	62,500-69,100	73,800	52,500-57,900	59,600	56,700
MSW	70,500-77,100	83,000	59,200-64,700	67,100	74,600

(1) BASED ON EPA HIGHWAY DRIVING CYCLE AND HIGHER HEATING VALUE OF FUELS; BASELINE GASOLINE VEHICLE CONSUMES 37,900 BTU/MI OF PETROLEUM.

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Table 4-18. Overall Resource Consumption for Heavy-Duty Diesel Vehicles

	RESOURCE CONSUMPTION, Btu/mi				
	DUAL-FUEL		SINGLE-FUEL		
RESOURCE	CNG	LNG	CNG	LNG	METHANOL
NATURAL GAS					
NG	26,800-29,500	31,100	38,300-42,200	42,700	57,000
PETROLEUM	7900	7900	-	-	-
TOTAL	34,700-37,400	39,000	38,300-42,200	42,700	57,000
COAL					
COAL	41,100-45,100	48,000	58,700-64,500	65,800	59,100
PETROLEUM	7900	7900	-	-	-
TOTAL	49,000-53,000	55,900	58,700-64,500	65,800	59,100
WOOD					
WOOD	43,400-47,900	51,200	62,100-68,500	70,200	65,000
PETROLEUM	7900	7900	-	-	-
TOTAL	51,300-55,900	59,100	62,100-68,500	70,200	65,000
MSW					
MSW	49,000-53,500	57,600	70,000-76,500	78,900	85,500
PETROLEUM	7900	7900	-	-	-
TOTAL	56,900-61,400	65,500	70,000-76,500	78,900	85,500

(1) BASED ON EPA HIGHWAY DRIVING CYCLE AND HIGHER HEATING VALUE OF FUELS; BASELINE GASOLINE VEHICLE CONSUMES 35,100 Btu OF PETROLEUM PER MI.

Table 4-19. Summary of Relative Resource Energy Consumption: Petroleum Versus Natural Gas Resource Base

	RELATIVE RESOURCE ENERGY CONSUMPTION					
		DUAL-FUEL		SINGLE-FUEL		
VEHICLE	BASELINE	CNG	LNG	CNG	LNG	METHANOL
LIGHT-DUTY						
SPARK-IGNITION	100	107-118	122	98-108	98	132
DIESEL	100	117-122	124	138-152	138	182
HEAVY-DUTY						
SPARK-IGNITION	100	102-112	118	85-94	96	131
DIESEL	100	99-107	111	109-120	122	162

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SECTION 5

POTENTIAL PETROLEUM DISPLACEMENT

This section analyzes potential fleet use of natural gas (NG) and methanol. It was assumed that widespread private use will not occur in the United States unless public fueling stations become commonly available. For NG, privately owned public stations are likely to follow major fleet use rather than precede it, since the stations are expensive and the market prospects are uncertain. That is one reason why fleets are emphasized here. Italian experience with compressed natural gas (CNG) has involved public use for about 40 years, but with a strong governmental involvement in such activities as design specifications, station siting, cylinder ownership, and inspection of gas cylinders.

This section begins with a summary of relevant data on domestic car, truck, and bus fleets. The number of fleet vehicles of various sizes and their fuel consumption are then projected. Next, the potential amount of petroleum fuel displaced by CNG, liquefied natural gas (LNG), and methanol is analyzed. Finally, factors which currently inhibit NG use in fleets are discussed.

5.1 PASSENGER CAR FLEETS

Fuel economy, annual mileage, and retention period data were compiled for six types of passenger car fleets: (1) business, (2) rental, (3) government (federal, state, and local), (4) police, (5) utility, and (6) taxi. An attempt was also made to compile these data for "large" fleets of 10 or more cars in each fleet type. The user economic calculations presented in Section 8 indicate that small fleets and individual owners may not presently be able to justify NG conversions on economic grounds alone if a fueling station must also be purchased.

5.1.1 Business Fleets

The principal source of business fleet information is Automotive Fleet Magazine. Table 5-1 shows the number of cars in large business fleets through 1981 (Ref. 5-1). The number has increased 25 percent over the last decade, but has remained nearly constant as a fraction of total car registrations. Company-leased cars comprise an increasing fraction of the business fleet, while the company-owned and sales-person-owned portion is diminishing.

Table 5-1. Historical Breakdown for U.S. Cars in Business Fleets of Ten or More Cars (Refs. 5-1 and 5-2)

CATEGORY	NUMBER OF CARS, MILLIONS						
	1971	1974	1977	1978	1979	1980	1981[1]
BUSINESS CARS IN FLEETS OF TEN OR MORE							
SALESPERSON-OWNED	0.411	0.373	0.353	0.350	0.348	0.345	0.340
COMPANY-OWNED	0.799	0.715	0.683	0.683	0.685	0.680	0.655
COMPANY-LEASED	1.336	1.814	2.031	2.091	2.141	2.234	2.192
TOTAL	2.546	2.902	3.067	3.124	3.174	3.259	3.187
TOTAL CAR REGISTRATIONS	83.1	92.6	99.9	103.0	104.7	104.2	103.9
FLEET CAR FRACTION OF REGISTRATIONS, PERCENT	3.06	3.13	3.07	3.03	3.03	3.13	3.07

(1) ESTIMATED FROM 1979 AND PRIOR YEAR DATA OF REF. 5-1.

Characteristics of company-leased vehicles are reported annually by the American Automotive Leasing Association (AALA), and Table 5-2 shows some of these data (Ref. 5-1). There is a trend toward longer vehicle retention and a general shift from standard-sized vehicles to intermediate and compact models. These data were used to estimate the current composition of the leased business fleet, as summarized in Table 5-3.

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Table 5-2. Characteristics of Company Leased Passenger Cars (Ref. 5-1)

CHARACTERISTIC	MODEL YEAR 1971	1974	1977	1978	1979	1980
MODEL MIX, PERCENT						
STANDARD	81	62	45	48	45	32
INTERMEDIATE	15	33	47	44	43	48
COMPACT	4	5	8	8	12	20
AVERAGE USAGE						
RETENTION PERIOD, MONTHS	NA	23.9	26.1	26.3	26.6	27.4
ANNUAL TRAVEL, 10^3 MI	NA	26.4	28.6	30.6	29.0	34.6

Table 5-3. Composition of Leased Business Fleets in 1981

SIZE CLASS	MIX, PERCENT 1979	1980	1981
LARGE	42	24	10
MIDSIZE	42	47	50
COMPACT	16	24	30
SUBCOMPACT	0	5	10
NOTE: MODEL YEAR MIX	10	45	45

Characteristics of company-owned fleets are compiled by the National Association of Fleet Administrators (NAFA) and are reported in Reference 5-3. NAFA is an organization of administrators of fleets of at least 25 cars or light trucks, and predominantly represents business fleet operators (Ref. 5-4). The 1980 NAFA survey indicated that acquisition plans for 1981 involved a shift toward compact and subcompact models.

Since NAFA survey respondents retain their cars an average of 31 months and 58 percent of these are leased (for a period of 27 months according to AALA), it was concluded that company-owned vehicles are retained for approximately 36 months. From these data and the trends of acquired vehicle sizes, the composition of company-owned fleets was estimated as shown in Table 5-4. A uniform model year distribution was assumed, consistent with the estimated 36 month average retention period for these vehicles.

Table 5-4. Composition of Company-Owned Business Fleets in 1981

SIZE CLASS	MIX, PERCENT 1979	1980	1981
LARGE	15	10	5
MIDSIZE	40	30	15
COMPACT	40	50	60
SUBCOMPACT	5	10	20
NOTE: MODEL YEAR MIX	33.3	33.3	33.3

Average on-road fuel economy for the fleets was estimated based on the sales-weighted EPA composite (city-highway) fuel economy given in Table 5-5 (Ref. 5-5). The improvement in EPA fuel economy with increasing mileage, in the early stages of a vehicle's life, was calculated using the following empirical relation (Ref. 5-6).

$$\text{EPA MPG}(M) = \text{EPA MPG}(4K) \times (0.846 + 0.0186 \ln M) \qquad (5\text{-}1)$$

In this equation, M is the odometer reading, while EPA MPG (4K) denotes the EPA fuel economy, which is measured on new cars after accumulation of 4000 miles. To account for the difference between EPA and on-road fuel economy, the EPA figures were then discounted by 18 percent. This is based on the results shown in Figure 5-1, which shows the measured

discrepancy between the EPA fuel economy and the average on-road automobile fuel economy of the same vehicles. Prior to model year 1978, the discrepancy was larger for high-fuel-economy vehicles. Since then, the range has narrowed to 15 to 19 percent. The resulting estimated average on-road automobile fuel economy is 19 mpg.

Table 5-5. Sales Weighted EPA Composite Fuel Economy, Domestic and Captive Import Cars (Ref. 5-5)

	COMPOSITE FUEL ECONOMY, MPG		
SIZE CLASS	1979	1980	1981
LARGE	17.7	19.6	20.9
MIDSIZE	19.1	21.1	22.8
COMPACT	19.4	22.9	29.1
SUBCOMPACT	23.5	25.1	26.0

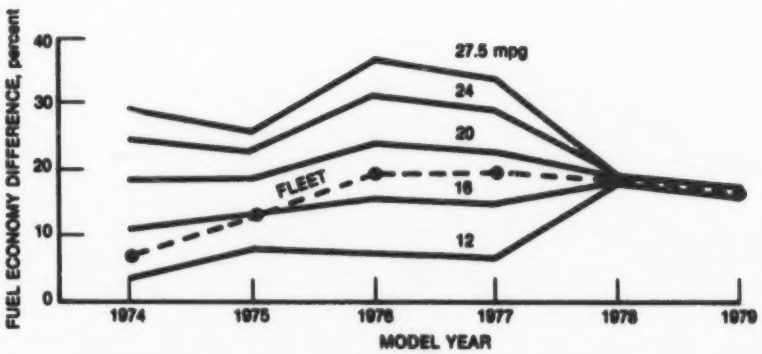

Figure 5-1. Fuel Economy Shortfalls between EPA Test and In-Use Data (Ref. 5-6)

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5.1.2 Rental Fleets

The rental fleet population was estimated based on the 1979 value reported by Automotive Fleet Magazine and an estimated 3 percent annual increase, for an estimated 491,000 vehicles in 1981 (Ref. 5-1). The average annual vehicle miles travelled (VMT) per vehicle was reported by Automotive Fleet Magazine as 16,300 miles (Ref. 5-7). The sales-weighted EPA composite fuel economy of 1981 model domestic cars was estimated as 23.7 mpg (Ref. 5-5), and discounted by 18 percent for on-road discrepancies. No odometer correction was employed, due to the relatively low mileages accumulated during the average 14-month retention period of these vehicles (Ref. 5-7).

5.1.3 Government Fleets

5.1.3.1 Federal

Federal fleet characteristics were obtained from the 1978 and 1979 Federal Motor Vehicle Fleet Reports (Ref. 5-8). The number of sedans and station wagons was assumed to remain at the 1979 value. The percentage increase in fuel economy from 1978 to 1979 was extrapolated to 1981. It should be noted that 94 percent of the GSA passenger vehicle acquisitions in 1979 were compact models.

5.1.3.2 State and Local

Estimates of the number of automobiles operated by state, county, and municipal governments were derived from statistics published annually by Automotive Fleet Magazine and by the Federal Highway Administration (FHWA) (Refs. 5-1 and 5-8). In 1979, FHWA estimated that state, county, and municipal fleets included 722,000 automobiles and 29,000 motorcycles. However, FHWA also noted that this information, compiled chiefly from reports of state authorities, is incomplete in many cases. Some states give state-owned vehicles only, while others exclude from registration certain classes, such as fire apparatus, and police vehicles. For the states not reporting state, county, and municipal vehicles separately from private and commercial vehicles and those

reporting unsegregated totals only, classification by vehicle type was approximated by FHWA on the basis of other available data (Ref. 5-9).

Automotive Fleet Magazine gave the size of the 1979 government fleet as 645,000 and identified an additional 291,000 police vehicles (Ref. 5-1). However, some light-duty trucks were included (Ref. 5-10). With light-duty trucks removed, these fleets were estimated to contain about 500,000 cars.

Average mileage estimates range from 14,000 to 17,000 miles annually. For this analysis, the high estimate was selected because it appeared to be the most recent (Refs. 5-11 through 5-13). The average retention period has been reported as 48 months (Ref. 5-13). No fuel economy data for these fleets were found, and an average value was estimated based on an assumed equal mix of compact and midsize cars.

5.1.4 Police Fleets

In 1977, the International Association of Chiefs of Police (IACP) conducted a survey of the vehicles used by the law enforcement agencies of the largest municipalities (cities and counties), and of 49 states (Ref. 5-14). The results are summarized in Table 5-6. Additional information was obtained from a 1980 IACP patrol car test report (Ref. 5-15) and from an administrative survey conducted by the Police Foundation (Ref. 5-16).

Table 5-6. Selected Characteristics of Police Fleets (Ref. 5-14)

POLICE TYPE	POPULATION, MILLIONS	NUMBER OF FLEETS	AVERAGE VEHICLES PER FLEET	PATROL CAR FRACTION, PERCENT	MOTORCYCLE FRACTION, PERCENT	ANNUAL TRAVEL PER VEHICLE, 10^3 MI	
						AVERAGE	RANGE
STATE	NA	40	800	85	1	27	18-70
LOCAL	0.1-0.25	29	131	73	6	21	10-80
LOCAL	0.25-0.5	22	259	81	7	23	16-70
LOCAL	0.5-1.0	11	664	68	4	19	16-50
LOCAL	OVER 1.0	10	960	74	3	24	18-60
ALL LOCAL	-	72	367	73	5	22	10-80

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It was assumed that the 40 state respondents to the IACP survey were representative of the total fleet, and the total state fleet size was thereby estimated as 40,000 vehicles, assumed to be sedans and station wagons. In-use fuel economy corresponded closely to the EPA composite values of the municipal patrol vehicles identified in Reference 5-14. This correspondence was used to estimate the current in-use fuel economy of the state police fleets.

The IACP survey indicates that patrol cars constitute 73 percent of municipal police fleets. These fleets averaged 5 percent motorcycles, and included unspecified numbers of light-duty trucks, buses, non-patrol sedans, and other vehicles. As an extreme example, the Los Angeles Police Department employs only 700 marked patrol cars but about twice as many detective cars and other cars used in crime follow-up work, out of a total fleet of approximately 3000 vehicles (Ref. 5-17). It was assumed for this study that cars are actually 85 percent of the total municipal police fleet of approximately 250,000 vehicles (the 291,000 police vehicles identified by Automotive Fleet Magazine less 40,000 state police vehicles), for an estimated total of 213,000 cars.

The survey found an average in-use fuel economy of 8.5 mpg in 1977 (Ref. 5-14). This is about 25 percent lower than the average EPA city fuel economy of these vehicles. The current fuel economy of municipal police sedans was assumed to reflect an average 1979 mid-size sedan with a small V-8 engine and automatic transmission. The corresponding EPA city fuel economy is 16 mpg, and the in-use fuel economy was estimated to be about 12 mpg.

5.1.5 Utility Fleets

There were 529,000 light-duty vehicles in utility fleets in 1979 (Ref. 5-1). Passenger cars constituted approximately 30 percent of this total (Ref. 5-10). Therefore, the number of passenger cars in the public utility fleets in 1981 was estimated to be about 160,000 cars. The average annual VMT per car is about 12,000 miles, as reported in the 1980 Transportation Energy Conservation Data Book (Ref. 5-12).

In-use fuel economy was calculated based on a fleet of 1975-1981 compact and midsize cars. EPA composite fuel economy, the in-use correction factor, odometer correction, and survival rate were considered in these calculations (Refs. 5-6 and 5-18). The resulting average in-use fuel economy of public utility cars is approximately 16 mpg.

5.1.6 Taxi Fleets

An analysis of taxicab operating characteristics was prepared by Wells Research Company for the DOT in 1977 (Ref. 5-19), based on 1973 and 1975 data furnished by members of the International Taxicab Association (ITA), which represents primarily large fleets (Ref. 5-20). Cabs in fleets smaller than ten accounted for only 4.3 percent of the ITA members' cabs in 1973, and only 2.2 percent in 1975 (Ref. 5-19). The analysis indicated that the taxi fleet data compiled by Automotive Fleet Magazine correspond to Motor Vehicle Manufacturers Association (MVMA) data on taxi fleets of four or more vehicles.

Rather than employ the ITA data, it was decided to extract the number of cabs in fleets of ten or more from the Automotive Fleet/MVMA totals. It was assumed that taxis in fleets of four to nine cabs account for 25 percent of the cabs in fleets of four or more. For comparison, cars in fleets of ten or more comprise less than half of the number of cars in fleets of four or more (Ref. 5-1). Annual VMT per cab is about 40,000 miles, according to Reference 5-12. In comparison, the drivers participating in a fuel economy study involving New York City taxicabs averaged 110 miles per shift, with an estimated average annual VMT of 72,000 miles (Ref. 5-21).

5.1.7 Car Fleet Summary and Projections

The previously discussed car fleet characteristics are summarized in Table 5-7, and projections of fleet automobile fuel consumption are shown in Table 5-8. For this analysis, the total number of fleet cars and the number in fleets of four or more were estimated as 12 and 10 percent, respectively, of the total car population projected by Du Pont's ESCON model (Ref. 5-22). Diesel car penetration was based on the moderate

projection of 20 percent of sales by 1985 in Reference 5-22, integrated over about 3 years to reflect the high fleet replacement rate. Fuel economy values were projected in accordance with the diesel technology advancement shown for light-duty trucks in the same reference. The diesel fuel economy was assumed to be 40 percent higher than for present gasoline vehicles, diminishing to a 25 percent advantage by 2000 because of expected engine technology advances. On-road fuel economy was assumed to increase from 82 to 88 percent of the EPA composite value by 1985. Annual car mileage was held constant at 23,000 miles per vehicle.

Table 5-7. Statistical Summary for Cars in Fleets of Ten or More in 1981

FLEET TYPE	NUMBER OF VEHICLES, THOUSANDS	AVERAGE TRAVEL PER CAR: ANNUAL, 10^3 MI	AVERAGE TRAVEL PER CAR: DAILY, MI, 5 DAYS/WK	AVERAGE TRAVEL PER CAR: DAILY, MI, 7 DAYS/WK	AVERAGE RETENTION PERIOD, MONTHS	FLEET FUEL ECONOMY, MPG
BUSINESS						
SALESPERSON-OWNED	340	25(1)	88(1)	63(1)	NA	19(1)
LEASED	2192	28	107	77	27	19
COMPANY-OWNED	655	18	69	49	36	19
DAILY RENTAL	491	16	61	44	14	19
GOVERNMENT						
FEDERAL	107	13	50	36	72(Max)	18
STATE AND LOCAL	500	17	65	47	48(1)	17
POLICE						
STATE	40	27	104	74	30(1)	18
LOCAL	213	25	96	68	36(1)	12
UTILITY	162	12	46	33	60(1)	16
TAXI	155	40	153	110	36(1)	14
TOTAL/AVERAGE	4855	23.4	90	64		

(1) ASSUMED TO REFLECT AVERAGE

Table 5-8 shows a very strong increase in fleet consumption of diesel fuel, to 0.36 million barrels per day (BPD) in the year 2000. A reduction in gasoline demand is projected to 0.58 million BPD in 2000, a decline of about 42 percent.

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Table 5-8. Projected Car Petroleum Fuel Consumption

PARAMETER	CALENDAR YEAR 1981	1985	1990	2000
FLEET CARS, MILLIONS				
TOTAL	12.59	12.94	14.04	15.6
FLEETS OF 10 OR MORE	4.85	4.95	5.33	5.87
DIESEL FRACTION OF FLEETS				
NEW CAR SALES	0.071	0.200	0.374	0.450
CUMULATIVE	0.05	0.162	0.346	0.448
ON-ROAD FUEL ECONOMY, MPG				
GASOLINE	17.9	20.8	21.3	22.3
DIESEL	25.1	28.7	28.8	29.0
FUEL CONSUMPTION, 10^6 BPD				
TOTAL FLEET CARS				
GASOLINE	1.00	0.78	0.65	0.58
DIESEL	0.04	0.11	0.25	0.36
TOTAL	1.04	0.89	0.90	0.94
FLEETS OF 10 OR MORE				
GASOLINE	0.39	0.30	0.24	0.22
DIESEL	0.01	0.04	0.10	0.14
TOTAL	0.40	0.34	0.34	0.36

5.2 TRUCK AND BUS FLEETS

Trucks and buses account for a large share of petroleum fuel consumption both in total quantity and in consumption per vehicle. The range of vehicle sizes is much broader than for cars, so there are many more vehicle categories to consider. This section analyzes vehicle number, mileage, and fuel consumption characteristics of each segment.

5.2.1 Truck Fleets

The Truck Inventory and Use Survey, taken every 5 years by the United States Department of Commerce, is the most complete compilation of statistics available on private and commercial trucks in use (Ref. 5-23).

It was used extensively in this study even though the data are for 1977. Table 5-9 shows key characteristics of the truck fleet. The truck weight categories are defined in Table 5-10 in terms of gross vehicle weight (GVW) ratings and corresponding weight classes. Table 5-9 shows that the light-duty truck category, at 18.8 billion gallons consumed annually, was the most important category in 1977, but heavy-heavy units averaged 8.7 times as many gallons per truck. Medium and light-heavy trucks combined consumed about 10 percent of the total truck fuel.

Table 5-9. 1977 Truck Statistics

TRUCK CATEGORY	NUMBER REGISTERED, MILLIONS	TRAVEL: ANNUAL TOTAL, 10^9 MI	TRAVEL: AVERAGE PER TRUCK, MI/YR	FUEL CONSUMPTION: TOTAL, 10^9 GAL/YR	FUEL CONSUMPTION: AVERAGE PER TRUCK GAL/YR	FUEL CONSUMPTION: AVERAGE PER TRUCK MPG
LIGHT						
GASOLINE	22.323	237.386	10.634	-	-	-
DIESEL	0.012	0.154	12.833	-	-	-
OTHER (1)	0.060	0.903	15.050	-	-	-
TOTAL	22.395	238.443	10.647	18.834	841	12.66
MEDIUM						
GASOLINE	1.548	15.640	10.103	-	-	-
DIESEL	0.022	0.388	17.636	-	-	-
OTHER(1)	0.013	0.122	9.385	-	-	-
TOTAL	1.583	16.150	10.202	2.095	1323	7.71
LIGHT-HEAVY						
GASOLINE	0.748	7.176	9.567	-	-	-
DIESEL	0.040	0.873	21.825	-	-	-
OTHER(1)	0.014	0.196	14.000	-	-	-
TOTAL	0.802	8.245	10.281	1.381	1722	5.97
HEAVY-HEAVY						
GASOLINE	0.556	6.835	12.293	-	-	-
DIESEL	0.870	42.738	49.124	-	-	-
OTHER(1)	0.007	0.110	15.714	-	-	-
TOTAL	1.433	49.683	34.671	10.482	7315	4.74
ALL TRUCKS						
GASOLINE	25.174	267.037	10.608	-	-	-
DIESEL	0.945	44.153	46.722	-	-	-
OTHER(1)	0.094	1.331	14.160	-	-	-
TOTAL	26.213	312.521	11.922	32.79	1251	9.53

(1) LPG, OTHER FUEL, AND UNREPORTED FUEL.

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Table 5-10. Definition of Truck Weight Categories

WEIGHT CATEGORY	GVW, LB	WEIGHT CLASS
LIGHT	0-10,000	1 & 2
MEDIUM	10,001-19,500	3, 4 & 5
LIGHT-HEAVY	19,501-26,000	6
HEAVY-HEAVY	>26,000	7 & 8

A few comments should be made concerning the survey. It provides detailed statistics by weight, type, fuel, annual mileage, daily range, configuration and number of axles, industry, fuel economy, fleet sizes, operator classification, engine size, etc. Nonetheless, some data needed for this section are not specified and were estimated and forced to fit the tabulated data by an iterative process. For example, the number of trucks in fleets of six or more is given by weight category for all fuels combined, and is also given by fuel type for all truck types combined. The number of gasoline trucks of a given type, however, is not given for any weight category or even the combined total. An approximate distribution was fitted by trial and error, as shown in Table 5-11. The fuel consumption calculated for the vehicles in fleets of six or more by two different approaches (truck type versus truck weight) yielded almost identical results. Another problem with the survey is that fuel economy data are presented in terms of number of vehicles and VMT within certain fuel economy ranges, rather than as averages. Average fuel economy values in this subsection are therefore approximate.

Large fleets were defined for this study as six or more trucks, similar to the choice of 10 or more for cars. The survey only included data for fleets of 1, 2 to 5, 6 to 19, and 20 or more. That is why six was selected instead of 10.

Comparison of Tables 5-9 and 5-11 reveals that most light-duty trucks are in fleets of five or less. For the other weight categories,

large fleets represent substantial fractions of the total, especially in the heaviest category where 59 percent are in large fleets. Truck-tractor combinations, mostly diesel powered, represent 60 percent of these trucks.

Table 5-11. Distribution of Trucks in Fleets of Six or More in 1977

TRUCK CATEGORY	NUMBER OF VEHICLES, THOUSANDS				
	LIGHT	MEDIUM	LIGHT-HEAVY	HEAVY-HEAVY	TOTAL
PICKUP					
GASOLINE	940	14	0	0	954
DIESEL	0	0	0	0	0
OTHER(1)	2	0	0	0	2
TOTAL	942	14	0	0	956(2)
PANEL					
GASOLINE	452	10	0	0	462
DIESEL	0	0	1	0	1
OTHER(1)	1	0	0	0	1
TOTAL	453	10	1	0	464(2)
MULTISTOP OR WALK-IN					
GASOLINE	84	35	1	0	120
DIESEL	0	0	2	0	2
OTHER(1)	0	0	0	0	0
TOTAL	84	35	3	0	122(2)
OTHER SINGLE UNIT					
GASOLINE	123	360	257	257	997
DIESEL	1	5	8	74	88
OTHER(1)	1	4	4	2	11
TOTAL	125	369	269	333	1.096(2)
TRUCK-TRACTOR COMBINATIONS					
GASOLINE	3	7	20	72	102
DIESEL	0	1	4	436	441
OTHER(1)	0	0	1	2	3
TOTAL	3	8	25	510	546(2)
TOTAL TRUCKS					
GASOLINE	1.602	426	278	329	2.635(3)
DIESEL	1	6	15	510	532(3)
OTHER(1)	4	4	5	4	17(3)
TOTAL	1.607(2)	436(2)	298(2)	843(2)	3.184(2)

(1) LPG, OTHER FUEL, AND UNREPORTED FUEL.
(2) FROM REFERENCE 5-23.
(3) THE DISTRIBUTION OF VEHICLES BY FUEL TYPE WAS ESTIMATED USING THE KNOWN TOTAL PROPORTIONS FOR EACH SIZE CLASS.

Table 5-12 shows the estimated fuel consumption in each weight category for the total truck population and for large fleets. The same fuel economy was assumed for the average vehicle in each of the weight categories, regardless of fuel type or fleet size. Reference 5-24

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indicates that negligible fuel economy differences existed between gasoline and diesel vehicles in the 1946-1976 period, for all weight classes, and this is attributed to the typically higher weight of diesel trucks within each weight class. The table shows that, with the exception of the light-duty trucks, trucks in large fleets consume 30 to 66 percent of the fleet total in each weight class. Their consumption exceeded 10 billion gallons in 1977, 60 percent of which was diesel fuel.

Table 5-12. Approximate Truck Fuel Consumption in 1977

	FUEL CONSUMPTION, 10^9 GALLONS						TOTAL 6 OR MORE AS FRACTION OF TOTAL, PERCENT
	TOTAL TRUCK FLEET			FLEETS OF 6 OR MORE			
TRUCK CATEGORY	DIESEL FUEL[1]	GASOLINE & OTHER	TOTAL	DIESEL FUEL	GASOLINE & OTHER	TOTAL 6 OR MORE	
LIGHT	0.012	18.814	18.826	0.001	1.814	1.815	9.64
MEDIUM	0.050	2.045	2.095	0.017	0 679	0.696	33.22
LIGHT-HEAVY	0.146	1.236	1.382	0.071	0.600	0.671	48.55
HEAVY-HEAVY	9.025	1.466	10.491	5.972	0.971	6.943	66.18
TOTAL	9.233	23.561	32.794	6.061	4.064	10.125	30.87

(1) REF. 5-24 INDICATES THAT 1946-1976 MEDIUM AND HEAVY TRUCKS DATA SHOW A NEGLIGIBLE DIFFERENCE IN FUEL ECONOMY BETWEEN DIESEL AND GASOLINE VEHICLES IN A GIVEN MODEL YEAR. LARGER LOADS AND ENGINE DISPLACEMENTS FOR DIESELS COULD ACCOUNT FOR THIS. FUEL QUANTITIES ARE THEREFORE DISTRIBUTED IN PROPORTION TO TRUCK-MILES.

Table 5-13 shows projections of total gasoline and diesel trucks in each weight class through the year 2000 and their average annual mileage (Ref. 5-24). A moderate diesel penetration rate was chosen for each weight group. By assuming that the large fleets will remain at the same fraction of the total in each weight and fuel category, the projections of Table 5-14 were obtained. A comparison of Tables 5-13 and 5-14 reveals that trucks in large fleets have a lower proportion of light-duty trucks, a higher proportion of the heavy-heavy trucks of high annual mileage, and greater annual mileage in each weight category. The result is a 72 percent higher annual mileage for trucks in fleets of six or more.

In Table 5-15, the large fleets are shown by truck type or configuration, and their operating characteristics are presented along with estimates of gasoline and diesel fuel consumption. Total fuel

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Table 5-13. Projected Truck Population (Refs. 5-23 and 5-24)

TRUCK CATEGORY	TRUCK POPULATION, MILLIONS 1977	1985	1990	2000	AVERAGE TRAVEL PER TRUCK, MI/YR
LIGHT					
GASOLINE	22.323	32.7	35.9	41.8	
DIESEL	0.012	1.8	6.8	22.0	
OTHER(1)	0.060	-	-	-	
TOTAL	22.395	34.5	42.7	63.8	10.650
MEDIUM					
GASOLINE	1.548	0.45	0.37	0.35	
DIESEL	0.022	0.02	0.06	0.20	
OTHER(1)	0.013	-	-	-	
TOTAL	1.583	0.47	0.43	0.55	10.200
LIGHT-HEAVY					
GASOLINE	0.748	1.04	0.80	0.28	
DIESEL	0.040	0.30	0.78	1.96	
OTHER(1)	0.014	-	-	-	
TOTAL	0.802	1.34	1.58	2.24	10.280
HEAVY-HEAVY					
GASOLINE	0.556	0.13	0.11	0.03	
DIESEL	0.870	1.70	2.20	3.41	
OTHER(1)	0.007	-	-	-	
TOTAL	1.433	1.83	2.31	3.44	34.700
TOTAL TRUCKS					
GASOLINE	25.174	34.2	37.2	42.4	
DIESEL	0.945	3.9	9.8	27.6	
OTHER(1)	0.094	-	-	-	
TOTAL	26.213	38.1	47.0	70.0	11.920

(1) LPG, OTHER FUELS, AND UNREPORTED FUEL

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Table 5-14. Projected Truck Fleets of Six or More (Ref. 5-23)

TRUCK CATEGORY	TRUCK POPULATION, MILLIONS 1977[1]	1985	1990	2000	AVERAGE TRAVEL PER TRUCK[1], MI/YR
LIGHT					
GASOLINE	1.602	2.35	2.58	3.00	
DIESEL	0.001	0.13	0.48	1.58	
OTHER[2]	0.004	—	—	—	
TOTAL	1.607	2.48	3.06	4.58	14,300
MEDIUM					
GASOLINE	0.426	0.13	0.10	0.09	
DIESEL	0.006	0.00	0.02	0.06	
OTHER[2]	0.004	—	—	—	
TOTAL	0.436	0.13	0.12	0.15	12,320
LIGHT-HEAVY					
GASOLINE	0.278	0.38	0.30	0.10	
DIESEL	0.015	0.12	0.29	0.73	
OTHER[2]	0.005	—	—	—	
TOTAL	0.298	0.50	0.59	0.83	13,450
HEAVY-HEAVY					
GASOLINE	0.327	0.10	0.06	0.02	
DIESEL	0.512	0.98	1.30	2.01	
OTHER[2]	0.004	—	—	—	
TOTAL	0.843	1.08	1.36	2.03	39,040
TOTAL TRUCKS					
GASOLINE	2.63	2.96	3.04	3.21	
DIESEL	0.53	1.23	2.09	4.38	
OTHER[2]	0.02	—	—	—	
TOTAL	3.18	4.19	5.13	7.59	20,500

(1) FROM REF. 5-23.
(2) LPG, OTHER FUELS, AND UNREPORTED FUEL.

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Table 5-15. Statistical Summary for Commercial Trucks in Fleets of Six or More in 1977 (Ref. 5-23)

PARAMETER	PICKUP	PANEL	MULTISTOP OR WALK-IN	OTHER SINGLE	TRUCK-TRACTOR COMBINATIONS	TOTAL
NUMBER, THOUSANDS						
GASOLINE	954	463	120	997	102	2636
DIESEL	0	0	2	88	441	531
OTHER(1)	2	1	0	11	3	17
TOTAL	956	464	122	1096	546	3184
AVERAGE TRAVEL PER TRUCK						
ANNUAL, 10^3 MI						
GASOLINE	14.5	14.7	14.7	12.5	15.6	13.8
DIESEL	-	-	-	29.6	59.4	54.3
DAILY @ 5 DAY/WK, MI						
GASOLINE	56	56	56	48	60	53
DIESEL	-	-	-	113	228	208
DAILY @ 7 DAY/ WK, MI						
GASOLINE	40	40	40	34	43	38
DIESEL	-	-	-	81	163	149
FLEET FUEL ECONOMY, MPG						
GASOLINE	14.4	14.4	11.4	6.0	3.9	-
DIESEL	-	-	15	8.0	4.6	-
FUEL CONSUMPTION, 10^9 GAL/YR(2)						
GASOLINE	0.96	0.47	0.16	2.08	0.41	4.08
DIESEL	0	0	0	0.33	5.71	6.04
TOTAL	0.96	0.47	0.16	2.41	6.12	10.12 (660.000 MPD)

(1) LPG, OTHER FUELS, AND UNREPORTED FUEL.
(2) EXCLUDES LPG, OTHER FUEL, AND UNREPORTED FUEL.

consumption matches that of Table 5-12. Not surprisingly, the combination trucks are shown to have consumed 60 percent of the total fuel of the fleets in 1977. Ninety-three percent of their consumption was diesel fuel. No other vehicle types consumed a significant fraction of diesel fuel.

Table 5-16 shows fuel economy projections through the year 2000, based on VMT and fuel consumption projections from Reference 5-22. These values were then applied to the entire private and commercial truck fleet and the large fleets in each weight category to obtain the projected fuel consumptions shown in Table 5-17. The results are shown graphically in Figures 5-2 and 5-3 for the total population and for fleet trucks, respectively. The smaller fraction of gasoline used by the fleet vehicles is obvious. Gasoline consumption dominates truck fuel usage currently in all but the heaviest truck weight category. Total gasoline consumption is

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Table 5-16. Truck Fleet Fuel Economy Projections

	FUEL ECONOMY, MPG									
	1977	1985			1990			2000		
TRUCK CATEGORY	TOTAL	GASOLINE	DIESEL	TOTAL	GASOLINE	DIESEL	TOTAL	GASOLINE	DIESEL	TOTAL
LIGHT	12.66	15.1	22.8	15.5	16.3	24.3	17.5	18.0	24.0	20.0
MEDIUM	7.71	7.8	9.3	8.3	8.6	15.0	9.4	10.2	14.5	11.6
LIGHT-HEAVY	5.97	5.2	7.8	6.0	5.2	8.3	7.0	6.5	8.5	8.4
HEAVY-HEAVY	4.74	3.7	4.9	4.8	3.7	5.1	5.1	-	5.5	5.5
AVERAGE	9.53	13.7	6.2	10.4	15.1	8.1	11.3	17.6	10.3	12.7
NOTE:										
FLEETS OF 6 OR MORE	6.50	10.41	5.18	6.47	12.25	5.85	6.93	16.59	6.71	7.63

Table 5-17. Projected Private and Commercial Truck Fleet Fuel Consumption

	FUEL CONSUMPTION, 10^9GAL/YR[1]											
	1977			1985			1990			2000		
TRUCK CATEGORY	GASOLINE	DIESEL	TOTAL	GASOLINE	DIESEL	TOTAL	GASOLINE	DIESEL	TOTAL	GASOLINE	DIESEL	TOTAL
ALL TRUCKS												
LIGHT	18.8	0.0	18.8	21.3	1.2	22.5	20.9	3.8	24.7	20.8	10.5	31.3
MEDIUM	2.0	0.1	2.1	0.6	0.0	0.6	0.5	0.1	0.6	0.4	0.2	0.6
LIGHT-HEAVY	1.2	0.2	1.4	2.5	1.1	3.6	1.7	2.5	4.2	0.4	4.8	5.2
HEAVY-HEAVY	1.5	9.0	10.5	0.6	16.9	17.5	0.3	21.2	21.5	0.0	28.8	28.8
TOTAL	23.5	9.3	32.8	25.0	19.2	44.2	23.4	27.6	51.0	21.6	44.3	65.9
FLEETS OF 6 OR MORE												
LIGHT	1.8	0.0	1.8	2.1	0.1	2.2	2.0	0.4	2.4	2.0	1.0	3.0
MEDIUM	0.7	0.0	0.7	0.2	0.0	0.2	0.2	0.0	0.2	0.1	0.1	0.2
LIGHT-HEAVY	0.6	0.1	0.7	1.2	0.5	1.7	0.8	1.2	2.0	0.1	2.4	2.5
HEAVY-HEAVY	1.0	5.9	6.9	0.4	11.2	11.6	0.2	14.0	14.2	0.0	19.0	19.0
TOTAL	4.1	6.0	10.1	3.9	11.8	15.7	3.2	15.6	18.8	2.2	22.5	24.7

(1) GASOLINE QUANTITIES INCLUDE LPG, OTHER FUELS AND UNREPORTED FUEL TYPES FROM REF. 5-23.

projected to diminish in absolute and relative terms through the year 2000, becoming insignificant in the heavy truck categories.

Government fleet trucks are the remaining sector to be considered. Table 5-18 presents available data on these vehicles (Refs. 5-8 and 5-9). The federal fleet vehicles average 5000 to 9000 miles annually. Total fuel consumption is only about 15,000 BPD. Available data are insufficient to evaluate the fuel consumption of the more numerous state and local government fleet vehicles.

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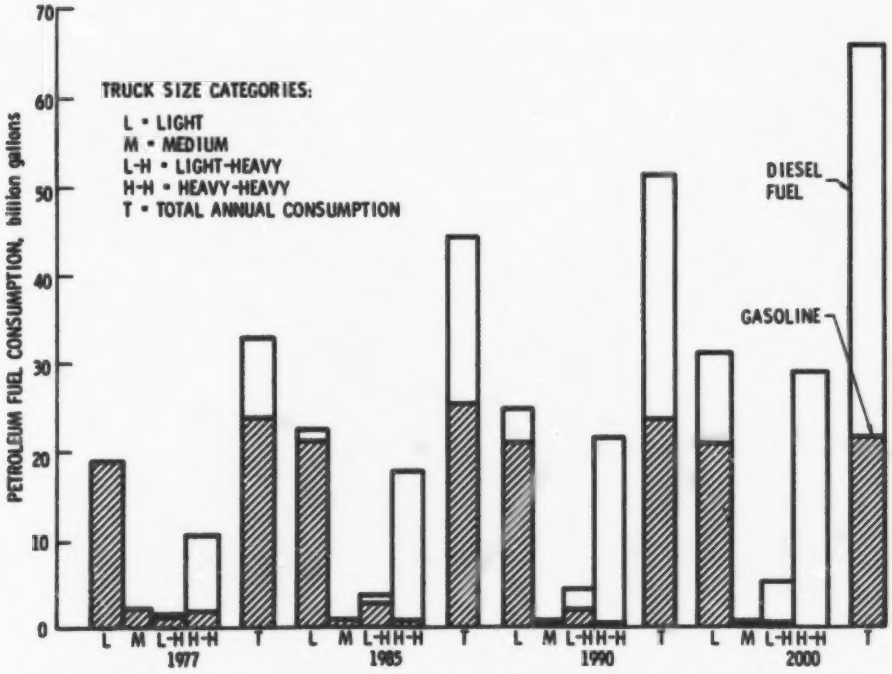

Figure 5-2. Projected Petroleum Fuel Consumption for Private and Commercial Trucks

5.2.2 Bus Fleets

The bus sector consists almost entirely of fleets with repetitive daily missions. They may therefore be particularly amenable to NG conversion and central fueling depots. As shown in Table 5-19, this sector can be divided into two basic categories: the large, diesel-engine-powered transit and intercity buses, and the smaller, spark-ignition (SI) engine-powered school buses (Refs. 5-25 and 5-26). The diesel buses, though smaller in number, have high average daily mileage and low fuel economy, and consume 60 percent of the fuel of this sector. The school buses are much more numerous, but are characterized by low daily mileage.

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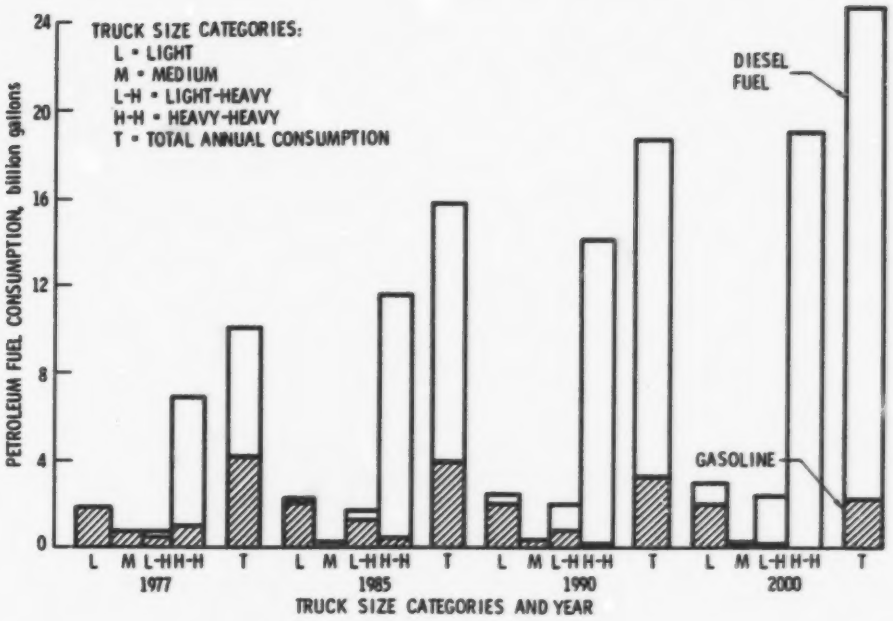

Figure 5-3. Projected Petroleum Fuel Consumption for Trucks in Fleets of Six or More

Table 5-18. Statistical Summary for Government Truck Fleets - 1979 (Refs. 5-8, 5-9)

TRUCK CATEGORY	NUMBER, THOUSANDS	AVERAGE TRAVEL PER TRUCK: ANNUAL, 10^3 MI	AVERAGE TRAVEL PER TRUCK: DAILY, MI, 5 DAYS/WK	AVERAGE TRAVEL PER TRUCK: DAILY, MI, 7 DAYS/WK	AVERAGE FUEL ECONOMY, MPG	FUEL CONSUMPTION, 10^6 GAL/YR
FEDERAL						
< 8,500 LB GVW	243	7.15	29	20	10.0	174
8,500-12,499 LB GVW	14	6.54	25	18	8.9	10
12,500-23,999 LB GVW	20	5.11	20	14	6.8	15
≥ 24,000 LB GVW	20	8.56	33	23	5.3	32
TOTAL	297	7.08	27	19		231 (15,100 BPD)
STATE AND LOCAL	1144					
TOTAL	1441					

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Table 5-19. Statistical Summary for Bus Fleets in 1978
(Refs. 5-25 and 5-26)

BUS TYPE	NUMBER, THOUSANDS			AVERAGE TRAVEL PER VEHICLE			AVERAGE FUEL ECONOMY,	FUEL CONSUMPTION, 10^6 GAL/YR		
				ANNUAL,	DAILY, MI					
	GASOLINE	DIESEL	TOTAL	10^3 MI	5 DAYS/WK	7 DAYS/WK	MPG	GASOLINE	DIESEL	TOTAL
TRANSIT	1	52	53	30.9	118	85	3.8	9	422	431
INTERCITY	0	20	20	53.6	206	147	6.0	-	180	180
SCHOOL/NON-REVENUE										
PRIVATE	145	0	145	7.5	29	21	7.4	148	-	148
PUBLIC	254	0	254	7.5	29	21		259	-	259
TOTAL/AVERAGE	400	72	472	12.1	46	33		416	602	1018
										(66,400 BPD)

5.3 PETROLEUM FUEL CONSUMPTION FOR FLEET VEHICLES

This subsection summarizes the results of the previous analyses of current and projected petroleum fuel requirements. In Table 5-20, the gasoline and diesel fuel consumption estimates are presented for each type of fleet vehicle through the year 2000. No projections were attempted for the relatively unimportant categories of government trucks and commercial/school buses. Using the data for large automotive fleets, it is seen that gasoline consumption should decline substantially by the year 2000, while diesel fuel consumption is projected to increase by an order of magnitude. Trucks in large fleets should almost halve their gasoline consumption, while diesel fuel consumption increases by 270 percent, to 10 times gasoline consumption. Today's combined fleet automobile and truck gasoline consumption of 10 billion gallons per year (GPY) will be almost halved by the year 2000, and the combined diesel fuel consumption of 6.3 billion GPY will increase to almost 25 billion GPY.

5.4 PETROLEUM DISPLACEMENT POTENTIAL

A summary of the potential petroleum fuel displacement by CNG, LNG, and methanol is shown in Table 5-21. For a dual-fuel conversion of an SI engine, virtually all of the gasoline can be displaced, except for that occasionally used to satisfy peak power demands and to keep

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Table 5-20. Projected Fleet Petroleum-Based Fuel Consumption

VEHICLE TYPE	PETROLEUM-BASED FUEL CONSUMPTION, 10^9 gal/yr							
	1977-1981		1985		1990		2000	
	GASOLINE	DIESEL	GASOLINE	DIESEL	GASOLINE	DIESEL	GASOLINE	DIESEL
FLEET AUTOMOBILES	15.37	0.58	12.0	1.7	9.9	3.9	8.9	5.5
FLEETS OF TEN OR MORE	5.91	0.22	4.6	0.6	3.8	1.5	3.3	2.1
PRIVATE AND COMMERCIAL TRUCKS	23.56	9.23	25.0	19.2	23.4	27.6	21.6	44.3
FLEETS OF SIX OR MORE	4.06	6.06	3.9	11.8	3.2	15.6	2.2	22.5
GOVERNMENT TRUCKS								
FEDERAL(1)	0.23 COMBINED		NO PROJECTIONS AVAILABLE					
STATE AND LOCAL(2)	UNKNOWN							
BUSES(3)								
TRANSIT AND INTERCITY	0.01	0.60						
SCHOOL	0.41	0						

(1) TOTAL POPULATION: 300,000 TRUCKS IN 1979
(2) TOTAL POPULATION: 1,140,000 TRUCKS IN 1978
(3) 1978 DATA

Table 5-21. Potential Displacement of Petroleum-Based Fuels by Alternative-Fuel Systems

ENGINE TYPE	PETROLEUM FUEL DISPLACED, PERCENT		
	CNG	LNG	METHANOL
GASOLINE	95(1)	95(1)	100
DIESEL(2)			
FUMIGATION(3)			
PASSENGER CARS	42	42	30
TRUCKS			
LIGHT	42	42	30
MEDIUM	53	53	37
LIGHT-HEAVY	65	65	46
HEAVY-HEAVY	76	76	54
DUAL-INJECTION(4)	-	-	40-72
EMULSIONS(5)	-	-	7-13

(1) ALLOWS FOR OCCASIONAL GASOLINE USE.
(2) CYCLE ENERGY DISPLACEMENT FACTOR VARIED FROM 0.5 FOR CARS TO 0.9 FOR HEAVY-DUTY TRUCKS.
(3) 85 PERCENT ENERGY DISPLACEMENT AT FULL LOAD WITH NG, 60 PERCENT WITH METHANOL.
(4) 80 PERCENT ENERGY DISPLACEMENT AT FULL LOAD.
(5) 30 PERCENT METHANOL BY WEIGHT.

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gasoline system seals and gaskets wetted and functional (Refs. 5-27 and 5-28). The 95 percent factor shown is higher than the average of about 75 to 80 percent CNG usage reported by current users. A methanol SI engine conversion would most likely be for a single-fuel system, and hence completely replace gasoline.

The primary alternatives with diesel engines are emulsions (methanol) with diesel fuel, fumigation, and dual injection. These offer different energy substitution capabilities, based on the review of diesel engine technology. For the techniques of NG or methanol use in diesel engines which have been evaluated to date, the replacement of diesel fuel is highest at full-load conditions. The pilot diesel fuel requirement tends to be constant even at reduced loads, so the effectiveness of NG or methanol addition diminishes. Power and efficiency of the diesel engine are reduced below that for normal diesel fuel operation at roughly half load, depending upon system design parameters and engine speed. The addition of NG or methanol may have to be curtailed under such conditions. Thus, for driving cycles which feature considerable low-power operation or idling, petroleum energy displacement would be significantly reduced. Table 5-21 provides preliminary estimates of a 90 percent cycle energy displacement factor for heavy-duty trucks and buses operating at high loads and constant speeds. For lightly loaded vehicles operating in urban areas, a factor of 50 percent is estimated. Detailed engine characterization and driving cycle analysis would be necessary to obtain more refined estimates.

In Table 5-22, the potential petroleum fuel displacement for the 1977 truck population in large fleets is estimated for both gasoline- and diesel-engine-powered vehicles. It assumes that all such vehicles are practical candidates for conversion. The petroleum fuel consumption values and energy substitution factors were previously discussed. The amounts of the alternative fuels required are expressed in energy-equivalent gallons of gasoline or diesel fuel, and also in their natural units.

Table 5-22. Potential Petroleum-Based Fuel Displacement for Trucks in Fleets of Six or More Based on 1977 Truck Data

Fuel Parameters	Gasoline Engines[1] L	M	L-H	H-H	Diesel Engines[2,3] L	M	L-H	H-H
Annual Consumption, 10^9 Gal	1.81	0.68	0.60	0.97	~0	0.02	0.07	5.97
Average Daily Consumption per Truck, Gal	3.10	4.37	5.91	8.13	2.7	9.1	12.79	31.95
Potential Petroleum Fuel Displacement, Percent								
CNG	← 95[4] →				42	53	65	76
LNG	← 95 →				42	53	65	76
Methanol	← 100 →				40	50	61	72
Petroleum Fuel Displaced per Truck by New Fuels[5]:								
CNG, Equivalent Gallons Petroleum Fuel	2.95	4.15	5.61	7.72	1.1	4.82	8.31	24.28
scf (Gasoline: 125 x Equivalent Gal)	372	523	707	973	160	699	1206	3523
(Diesel: 145 x Equivalent Gal)								
No. of Cylinders @ 325 scf/cyl	1.14	1.61	2.17	2.99	0.49	2.15	3.71	10.84
LNG, Equivalent Gallons Petroleum Fuel	2.95	4.15	5.61	7.72	1.1	4.82	8.31	24.28
Gallons (Gasoline: 1.541 x Equivalent Gal)	4.55	6.40	8.65	11.90	2.0	8.56	14.75	43.27
(Diesel: 1.775 x Equivalent Gal)								
Methanol, Equivalent Gallons Petroleum Fuel	3.10	4.37	5.91	8.13	1.1	4.55	7.80	23.00
Gallons (Gasoline: 2.049 x Equivalent Gal)	6.35	8.95	12.11	16.66	2.6	10.74	18.41	54.28
(Diesel: 2.360 x Equivalent Gal)								

(1) Natural gas (dual-fuel) or methanol (single-fuel) admitted by carburetion or fuel injection.
(2) Natural gas admitted by fumigation: up to 85 percent energy displacement at full load. Methanol admitted by dual-fuel injection into cylinders: up to 80 percent energy displacement at full load.
(3) Driving cycle energy displacement factor ranged from about 0.5 for cars and light trucks to 0.9 for heavy-heavy trucks.
(4) Typical levels of displacement are currently 75-80 percent.
(5) Daily displacement per truck at equal energy consumption rates (Btu/mi).

As shown in Table 5-22, light-duty truck consumption in 1977 was approximately 1.8 billion GPY of gasoline, averaging 3.1 gallons per truck per day. Heavy-heavy truck consumption was 6.9 billion GPY (86 percent diesel fuel), with daily averages of 8.1 gallons for gasoline trucks and 32.0 gallons for diesel trucks. Diesel fuel usage was heavily focused in the heavy-heavy category (over 98 percent) and accounted for 60 percent of all petroleum fuel used by fleets of six or more trucks.

Table 5-22 also shows the quantities of CNG, LNG, and methanol which could be substituted for gasoline, or for diesel fuel with advances in technology. The table reveals no significant problems for conversion of SI-engine-powered trucks. A daily filling of three CNG cylinders of 325 scf capacity each is sufficient to meet the fuel needs of even the average heavy-heavy SI truck. For diesel trucks the average requirement is four

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cylinders for light-heavy trucks and 11 cylinders for heavy-heavy trucks. In the important heavy-heavy truck size category, by the year 2000 daily gasoline quantity per truck is projected to decline by 32 percent and diesel fuel by 19 percent. In the light-duty truck category, gasoline use per truck will drop about 41 percent to 1.8 gallons per day, essentially the same consumption as for diesel vehicles.

It should be noted that the average daily mileages cited are minimums, based upon truck operation 365 days per year. Average mileage and fuel requirement per operating day are about 50 percent higher if a 5-day work week is considered with additional idle time for holidays, maintenance, and repairs.

Table 5-23 summarizes fuel consumption projections for the 1985 fleets of passenger cars and private and commercial trucks, and estimates potential petroleum displacement by CNG and LNG. The petroleum displacement factor includes two considerations: (1) the fraction of fuel consumed by vehicles in large fleets, and (2) the potential petroleum displacement per affected vehicle.

Table 5-23. Potential Petroleum-Based Fuel Displacement in 1985 by Natural Gas Fleet Cars and Private and Commercial Trucks

VEHICLE TYPE	NUMBER, MILLIONS	1985 FUEL CONSUMPTION, 10^9 GAL		CNG OR LNG PET. DISPL. FACTORS		POTENTIAL PETROLEUM-BASED FUEL DISPLACED, 10^9 GAL		
		GASOLINE	DIESEL	GASOLINE	DIESEL	GASOLINE	DIESEL	TOTAL
FLEET CARS	13	12.0	1.7	0.36	0.16	4.32	0.27	4.59
PRIVATE & COML. TRUCKS								
LIGHT		21.3	1.2	0.09	0.03	1.92	0.04	1.96
MEDIUM		0.6	0.0	0.32	0.18	0.19	0.00	0.19
LIGHT-HEAVY		2.5	1.1	0.46	0.32	1.15	0.35	1.50
HEAVY-HEAVY		0.6	16.9	0.63	0.50	0.38	8.45	8.83
TOTAL TRUCK	38	25.0	19.2			3.64	8.84	12.48
TOTAL	51	37.0	20.9	-	-	7.96	9.11	17.07
NOTE: COMBINED CARS & LIGHT TRUCKS	47	33.3	2.9	-	-	6.24	0.31	6.55

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The multiplication of the projected gasoline and diesel fuel consumptions by the corresponding fuel displacement factors produced the potential fuel displacements shown for each vehicle category in Table 5-23. These represent upper limits with no consideration of other factors which might prevent total fleet conversion to NG. In particular, technology advances would be required to permit large-scale diesel conversion for highway vehicles. Other factors include institutional barriers, competition from other alternative fuels, acceptability of reduced power output, fuel tank packaging requirements, availability of funds, availability of conversion or fueling station equipment in adequate quantities to meet 1985 timing, remaining useful life of vehicles, and mission constraints precluding centralized fueling, as discussed in Subsection 5.5.

The principal conclusion from Table 5-23 is that trucks have a greater petroleum displacement potential than cars when the heavy-heavy Class 8 diesel trucks are included. Excluding Class 8 trucks, which are typically long-haul vehicles and therefore would require many fueling stations, and which require technology advances for diesel applications, only gasoline applications show significant petroleum displacement potential. If all cars in fleets of 10 or more and all trucks in fleets of 6 or more were converted, the total petroleum displacement is estimated to be 17 billion GPY or 1.1 million BPD in 1985. Excluding diesel vehicles, which require technology advances to use NG, annual petroleum savings of about 8 billion GPY (0.5 million BPD) would result. For comparison, total highway vehicle fuel consumption in 1985 was estimated at 105 billion GPY, based on DOE projections given in Reference 5-29. The potential displacement by NG is 16 and 8 percent of this total, respectively.

If sufficient methanol were available and distributed through retail stations, it could potentially displace 8 billion GPY of gasoline and about 9 billion GPY of diesel fuel in 1985 in large-fleet applications. This represents about 8 and 9 percent, respectively, of the projected highway vehicle total. However, the corresponding methanol production requirement of about 15 to 35 billion GPY far exceeds the projected supply.

5.5 MARKET PENETRATION CONSIDERATIONS

Despite the fact that CNG conversion equipment has been available domestically for a decade, and successfully used in Italy for a much longer period, only about 20,000 cars and trucks have been converted in the United States. Many factors are responsible for this relatively small market penetration. Some of these factors, such as a concern about adequate nationwide supplies, may be of lesser importance now than in the past. Gasoline price increases during a period of NG price controls has, in the past few years, prompted more conversions. However, future NG prices are uncertain, with gradually decontrolled prices coinciding with a period of excess gas capacity and declining demand. In addition, LPG conversions have made strong inroads in the truck and OEM vehicle market.

This subsection highlights design, configuration, and operational considerations affecting the decisions of fleet operators to convert to NG. These factors are based on many discussions with users conducted during this study.

5.5.1 Gas Availability and Quality

NG is available to 160 million U.S. customers or 70 percent of the population (Ref. 5-30). Some fleet conversions will therefore be precluded by NG non-availability. Interstate pipeline NG will probably have acceptable hydrogen sulfide (H_2S) levels, though no conclusive data are available. Since there is evidently sufficient moisture in some gas to cause regulator icing, methanol addition during compression has been widely employed (Refs. 5-31 through 5-34). Intrastate gas quality may not be as high, since it need not meet interstate pipeline company specifications. In addition, oil is added to NG in some distribution systems to maintain pipeline sealing.

5.5.2 Conversion Hardware

At least five domestic CNG conversion kit manufacturers and one LNG kit manufacturer are currently providing equipment for the U.S. market, and some are serving foreign markets as well. Both domestic and

foreign hardware is used in key items such as CNG cylinders and pressure regulators. No special difficulties are expected in accommodating an expanded demand for conversion kits for carbureted SI engines. However, kits are not yet commercially available for use on vehicular diesel engines, or fuel-injected SI engines, although no problem is expected for the latter.

To date, Dual Fuel Systems, Inc., has received California Air Resources Board (CARB) certification, and thereby EPA certification, for the sale of its CNG equipment for domestic SI vehicles. Other producers are offering kits for sale in other states, apparently with the concurrence of appropriate state agencies. Their performance and emission data are generally not available. However, the EPA is not yet actively enforcing compliance of add-on equipment requirements of no increase in exhaust emissions.

5.5.3 Vehicle Performance, Operation and Emissions

In order to accommodate the lower acceleration of CNG-powered vehicles, the largest user, Southern California Gas Company (SCGC) selects the largest available engine for a given vehicle size and the highest numerical axle ratio, and does not purchase small pickup trucks offered with only small 4-cylinder engines (Refs. 5-33 and 5-35). SCGC also rules out tanks in the passenger compartment, including station wagons and vans, unless tanks are beneath the floor or in a vented enclosure box.

Some vehicles may experience an increase in emissions when operating on gasoline, which may occur up to 50 percent of the time (Ref. 5-34). This might place the vehicle above certification limits due to the added vehicle weight and the altered engine tuning typically required for compatible CNG/gasoline operation.

5.5.4 Conversion Costs and Siting Considerations

The size of fleet required to justify conversion depends primarily on the specific situation and on the projected prices of gasoline and NG, the cost of compression, storage and fueling equipment,

the cost of the necessary facility, interest rates for borrowed money, and necessary return on investment. Section 8 examines in detail the effect of these factors on overall conversion economics.

Costs of vehicle and station equipment are significant, precluding some organizations from making a full conversion in a reasonable period of time. ARA, Inc., though convinced of the favorable economics of CNG conversion (about 100 vehicles converted by June 1981), nonetheless expects to budget only about $3 million for conversion next year, sufficient for roughly 1000 vehicles or 5 percent of its 20,000-vehicle fleet. Its vehicles must have at least 2 years of remaining operational life and an annual mileage of 15,000 to 40,000 miles (Ref. 5-36).

One large police fleet has a requirement that all of its vehicles must operate on a single fuel. It cannot now incorporate diesel vehicles into its fleet and would have the same problem with CNG, LNG, or methanol (Ref. 5-17).

5.5.6 Other Motivations and Disincentives for Vehicle Conversions

The principal advantages and disadvantages cited by vendors and users were discussed Section 3 and are again summarized here in Table 5-24. The primary stated advantage is the great reduction in fuel costs experienced to date. If this advantage continues, it will provide a strong incentive for fleet operators to convert, as discussed in more detail in Section 8.

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Table 5-24. Operational Experience with Natural-Gas-Fueled Vehicles

ADVANTAGES	DISADVANTAGES
GREATLY REDUCED FUEL COSTS	GREATLY REDUCED DRIVING RANGE ON CNG
ENGINE LIFETIME EXTENDED	REDUCED ENGINE POWER REQUIRES LARGER ENGINES, HIGHER NUMERICAL FINAL DRIVE RATIO
EASY STARTING AND ENHANCED COLD-START DRIVEABILITY	CYLINDER WEIGHT AFFECTS STEERING AND MAY REQUIRE SUSPENSION CHANGES
SUBSTANTIALLY INCREASED SPARK PLUG LIFE	CYLINDERS OCCUPY NEEDED TRUNK SPACE
OIL CHANGE INTERVALS EXTENDED TO 25,000 MI	FREQUENT ENGINE/CNG SYSTEM TUNING FOR GOOD PERFORMANCE
REDUCED ENGINE MAINTENANCE BECAUSE OF NO CARBON BUILDUP	ENGINE KNOCKING IN GASOLINE MODE
REDUCED FUEL PILFERAGE	

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6. FUEL SUPPLY

A key issue in assessing natural gas (NG) as an automotive fuel is whether or not adequate supplies at acceptable prices will be available during the next 20 years. Domestic experience over the past decade underscores the importance of the question. During the early part of the 1970s, NG curtailments had begun to reduce industrial use of, and reliance on, NG. By the mid-1970s, particularly after the severe winter of 1976-77, the federal government had largely written off NG as a future energy source (Ref. 6-1). However, by 1979, with passage of the Natural Gas Policy Act (NGPA) of 1978, the situation had improved markedly. For the first time in five years, the decline in NG production leveled off. For the first time in six years, gas sales in all markets - residential, commercial, and industrial - were on the rise (Ref. 6-2). The outlook for NG supplies has changed so radically during 1981 that plans for several supplemental sources of high-Btu gas from coal, such as the WyCoalGas Project, have been suspended, at least temporarily (Ref. 6-3).

In this section, gas supply prospects for the next two decades are examined. First, published reserve figures for conventional and unconventional NG are presented and compared. Inasmuch as synthetic (or substitute) natural gas (SNG) and methanol can be manufactured from coal, biomass, and municipal solid waste (MSW), the availability of these resources will also be reviewed. In addition, some data will be presented on world-wide gas reserves, since there is the possibility of expanded gas imports to the United States.

The second general area addressed is the technology for processing NG, and producing SNG and methanol from the several raw materials. Only a short summary is presented in this section, but detailed process descriptions are provided in Volume III, Appendix C.

The final topic examined in this section is the projected supply and price of gas. The data were found in the recent literature and are not intended to be exhaustive; rather, they illustrate the divergence

of opinion on future gas availability and cost. Similar but less detailed information was prepared for methanol, a liquid fuel producible from NG or the same resources as SNG.

6.1 RESOURCES AND RESERVES

The total resource base of any recoverable mineral is composed of the reserves that have been found plus the potential resources yet to be discovered (Ref. 6-4). Definitions of "reserves" and the quantitatively larger "resources" vary among authors; Table 6-1 presents a list that encompasses the usual interpretations. Part of the resource, of course, may never be found, and large quantities that have been or will be found will never be produced because of economic or technological constraints (Ref. 6-4).

It should be noted at the outset that there has been a considerable lack of agreement in published estimates of reserves and resources, including some substantial revisions from year to year by particular authors. Because of the underlying uncertainty in such estimates, it is often necessary to give a fairly wide range of values rather than a single number. Even when a single number is generally accepted, it should be considered to have an uncertainty of at least ±10 percent. Part of the difficulty arises from inconsistencies in what is included in reserves and resources, and part is due to insufficient measurements. Some extensive regions have been inadequately explored, so the currently known potential does not necessarily indicate the true value. Furthermore, changing economic conditions and improvements in technology affect the economic recoverability of resources, which is a factor in the evaluation of proved reserves (Ref. 6-5).

6.1.1 Conventional Natural Gas

For proper perspective, it is necessary to examine the domestic NG position within the world community. Table 6-2 lists the 19 largest proved gas reserves. The United States reserves rank third, representing less than 10 percent of the world total. As shown in Table 6-3, the United States is the largest gas producer (and the largest

Table 6-1. Definition of Resource and Reserve Categories (Ref. 6-4)

Term	Category	Subcategory	Definition
Resources			Concentrations of valuable materials in forms that currently or potentially can be economically extracted
	Identified		Specific resources whose location, quality, and quantity are known from geologic evidence including exploratory probes
	Undiscovered		Unspecified resources presumed to exist on the basis of broad geologic knowledge and theory, but not yet identified by drilling
		Probable	Resources expected to occur in known productive areas, either as extensions of identified deposits or in known areas of mineralization
		Possible	Estimated resource in undiscovered or partly defined deposits, in formations or geologic settings within known productive provinces or subprovinces
		Speculative	Estimated resources in undiscovered or partly defined deposits, in formations or geologic settings not previously productive
Reserves			Identified deposits of minerals known to be recoverable with current technology and economic conditions
	Proved		Identified sources from which a material can be economically extracted with existing technology, and whose location, quality, and quantity are known on the basis of geologic and engineering evidence

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Table 6-2. Major World Gas Reserves as of 1 January 1981 (Ref. 6-6)

COUNTRY	ESTIMATED PROVEN RESERVES	
	ABSOLUTE, TCF	PERCENT OF TOTAL
U.S.S.R	920.0	34.9
IRAN	485.0	18.4
UNITED STATES	191.0	7.2
ALGERIA	131.5	5.0
SAUDI ARABIA	110.0	4.2
CANADA	87.3	3.3
MEXICO	64.5	2.4
NETHERLANDS	62.0	2.4
QATAR	60.0	2.3
NORWAY	42.7	1.6
VENEZUELA	42.0	1.6
NIGERIA	41.0	1.6
KUWAIT	30.8	1.2
AUSTRALIA	30.0	1.1
IRAQ	27.4	1.0
U.K.	24.8	0.9
CHINA	24.5	0.9
LIBYA	23.8	0.9
ARGENTINA	22.0	0.8
SUBTOTAL	2,420.3	91.7
OTHERS	218.2	8.3
TOTAL	2,638.5	100.0

consumer) in the world. An important statistic is the ratio of proved reserves to annual production, shown in Table 6-4 for those countries for which data are available. Except for China, where reserves are not well defined, the United States at 9.4 years has the lowest supply of all major producers. However, there is some basis for optimism in the reserve picture.

Table 6-3. Major Gas-Producing Countries (Ref. 6-6)

COUNTRY	1980 GAS PRODUCTION ABSOLUTE, TCF	PERCENT OF TOTAL
UNITED STATES	20.27	34.6
U.S.S.R.	15.35	26.2
CHINA	3.47	5.9
NETHERLANDS	2.80	4.8
CANADA	2.67	4.5
UNITED KINGDOM	1.50	2.6
MEXICO	1.19	2.0
ROMANIA	1.18	2.0
INDONESIA	1.03	1.7
WEST GERMANY	0.74	1.3
NORWAY	0.70	1.2
BOLIVIA	0.63	1.1
PAKISTAN	0.60	1.0
ITALY	0.52	0.9
VENEZUELA	0.52	0.9
ALGERIA	0.52	0.9
SUBTOTAL	53.69	91.6
OTHERS	4.95	8.4
TOTAL	58.64	100.0

Table 6-4. Supply of Proved Natural Gas Reserves at Current Production Rate (as of 1 January 1981)

COUNTRY	PROVED RESERVES AT PRESENT PRODUCTION RATE, YEARS
CHINA	7.1
UNITED STATES	9.4
NETHERLANDS	22.1
CANADA	32.7
U.S.S.R	59.9
MEXICO	76.8
VENEZUELA	81.1
ALGERIA	254.4

The NGPA was passed in 1978 to provide pricing incentives for increased drilling activity, to remove traditional barriers between intrastate and interstate markets, and to pave the way toward eventual gas decontrol. Although the NGPA raised wellhead prices for most types of gas, the average price is still substantially below that of competing fuels (Ref. 6-7). Despite the fact that recent incentives for oil drilling have outweighed those for gas drilling, the industry drilled 13,064 gas wells in 1979 compared with 11,278 in 1978, and well completions in 1980 were near 15,000. The result has been a change in the rate of decline of proved reserves, as shown in Figure 6-1. Proved gas reserves dropped by just 3 trillion cubic feet (TCF) in 1980, the lowest decline in a decade (Refs. 6-6 and 6-8).

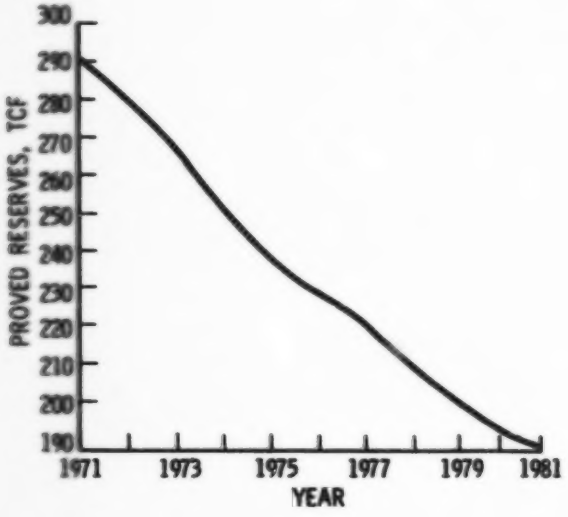

Figure 6-1. United States Proved Natural Gas Reserves, 1971 to 1981 (Refs. 6-6, 6-8)

In addition to proved reserves, there is a much larger, albeit more uncertain, quantity of potential NG resources. A recent estimate by the Potential Gas Committee for the United States, given in Table 6-5, indicates that 913 TCF of conventional NG remain to be produced, or the

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Table 6-5. Potential Natural Gas Resource as of 1 January 1981 (Ref. 6-9)

SOURCE	ESTIMATED UNDISCOVERED NATURAL GAS, TCF			
	PROBABLE	POSSIBLE	SPECULATIVE	TOTAL
ON SHORE (DRILLING DEPTH)				
LOWER 48 STATES				
LESS THAN 15,000 FT	116	161	94	371
15,000 TO 30,000 FT	35	103	102	240
ALASKA				
LESS THAN 15,000 FT	6	16	28	50
15,000 TO 30,000 FT	-	-	-	-
TOTAL ONSHORE	157	280	224	661
OFFSHORE (WATER DEPTH)				
LOWER 48 STATES				
LESS THAN 200 M	32	43	35	110
200 TO 1,000 M	2	22	23	47
ALASKA				
LESS THAN 200 M	2	13	68	83
200 TO 1,000 M	-	-	12	12
TOTAL OFFSHORE	36	78	138	252
TOTAL U.S.	193	358	362	913
NOTE:				
TOTAL LOWER 48 STATES	185	329	254	768
TOTAL ALASKA	8	29	108	145

equivalent of more than 45 times current annual production. Other estimates range up to approximately 60 years of production (Ref. 6-10). These potential supplies are in addition to proved reserves.

All the preceding estimates are for conventional gas deposits, but much of such gas is not easily recoverable. Approximately 16 percent of the potential gas is in Alaska, with the remainder in the lower 48 states. Within the lower 48 states, 41 percent of the potential gas is in shallow onshore regions, 26 percent at depths of more than 15,000 feet, and 17 percent in the Outer Continental Shelf (OCS). Thus, 59 percent of

the United States gas potential is located in hard-to-develop areas. Recent activity, however, is predominately onshore shallow well completions in the lower 48 states. Approximately 90 percent of the completions are in regions that contain only 30 percent of the remaining resources. Deep well and OCS drilling are not matching their estimated gas potential, and the Alaskan well completions are barely discernible (Ref. 6-10).

6.1.2 Unconventional Natural Gas

Unconventional natural gas, sometimes termed non-conventional gas, generally encompasses gas found in coal seams, Devonian shale, geopressured brines and tight gas reservoirs (Ref. 6-11). Occasionally, gas from other sources is included in this category, e.g., from in situ coal gasification, peat and oil-shale gasification, or from biomass, urban wastes, and animal residues. In this report, the more usual classification will be followed, with gas derived from more exotic sources assigned to other categories.

The gas resource in coal seams, Devonian shale, geopressured brines, and tight-gas reservoirs is estimated to be very large. Although technology for extracting gas from these sources is being developed, it is not yet possible to identify all the potential technical and environmental problems, nor to estimate production levels and costs with high accuracy. The following subsections briefly review these sources.

6.1.2.1 Gas from Coal Seams

Coal-bed gas is a natural by-product of coal formation. Although a large portion of the original gas has escaped to the atmosphere, a part is still trapped in place. Methane generally comprises 85 to 99 percent of the gas by volume. Coal-bed gas contains only a small portion (less than 2 percent) of the total energy of the host coal-bed (Ref. 6-11).

Only limited coal-seam gas content data are available and they pertain mostly to known, gassy, bituminous coals. Table 6-6 presents coal gas resource estimates based on published United States Geological Survey

(USGS) resource data, totalling 398 TCF (Ref. 6-11). Other authors set the total gas resource base as high as 500 TCF, with the maximum recoverable gas estimated at 10 to 60 TCF (Ref. 6-10).

The major techniques for recovering coal-bed gas are (1) hydraulically stimulated vertical wells, (2) unstimulated horizontal holes from vertical shafts, (3) unstimulated horizontal holes from mine access, and (4) slant holes that terminate with long horizontal in-seam segments. In the near-term, only methods (1) and (2) are economically feasible. Gas production from horizontal holes (2) is substantially greater than from hydraulically stimulated vertical wells in the same seam (1). Gas production of up to 30,000 standard cubic feet (scf) per day per 100 feet of horizontal hole length, and hole lengths exceeding 1000 feet, have been reported (Ref. 6-11). Production methods are discussed in detail in Appendix C.

Table 6-6. Estimated Coal-Bed Gas Resources (Ref. 6-11)

CATEGORY	ESTIMATED RESOURCES: COAL, 10^9 SHORT TONS	GAS CONTENT, FT^3/TON	COAL-BED GAS, TCF
300-3,000 FEET DEEP(1)			
ANTHRACITE	46	200	9
BITUMINOUS	1,001	200	200
SUBBITUMINOUS	1,137	80	91
LIGNITE	504	40	20
SUBTOTAL	2,688	119	320
3,000-6,000 FEET DEEP(2)	388	200	78
TOTAL/AVERAGE	3,076	129	398

(1) INCLUDES BOTH IDENTIFIED AND UNDISCOVERED
(2) UNDISCOVERED

Problem areas include (1) the need for improved drilling technology, (2) disposal of coal-bed water when encountered, (3) ownership of

the gas, which is awaiting court resolution, and (4) uncertainties about the production rate and life of coal-bed gas. Recovery costs may be low since they could be charged to mine safety. The primary use of these resources is expected to be in the local area.

6.1.2.2 Devonian Shale Gas

Known deposits of Devonian shale gas in the United States are primarily concentrated in the Appalachian, Michigan, and Illinois basins. The only significant data available relate to the brown shales of the Appalachian Basin. Although the average thickness of the shale deposits in this basin is much greater than that in the other two, a large part of the deposits consist of poorer-quality gray shale (Ref. 6-11).

Resource size estimates vary widely. In Reference 6-10, the probable range of technically recoverable gas from the Appalachian shales is estimated at 60 to 600 TCF; secondary shale deposits could well double this. The National Petroleum Council estimated the resource potential in the Appalachian Basin as 225 to 1861 TCF, while estimates for the Michigan and Illinois basins were 76 and 86 TCF, respectively (Ref. 6-11). As pointed out in both references, in-place gas is not a recoverable resource but only provides a means of ranking the shale gas potential of the three basins.

An estimate of the gas recoverable at various market prices and technology levels is given in Table 6-7, as provided by the American Gas Association (Ref. 6-10). Similar projections by the National Petroleum Council used historical production data from approximately 2700 out of some 9000 shale wells operating in Kentucky, West Virginia, Ohio, and New York as the basis for estimating future production, resulting in the estimates shown in Table 6-8.

Most Devonian shale wells require stimulation to produce at an economic level. The traditional technology is well-bore shooting. This method of stimulation is relatively inexpensive, and is satisfactory where favorable geologic conditions exist. Over the last 10 to 15 years, conventional hydraulic fracturing technology has been adapted to stimulate

Table 6-7. Estimated Recoverable Shale Gas Resources (Ref. 6-10)

MARKET PRICE, $/MCF (1979 DOLLARS)	ESTIMATED RECOVERABLE SHALE GAS RESOURCES, TCF	
	EXISTING TECHNOLOGY	ADVANCED TECHNOLOGY
$3.00	10	20
$4.50	15	30
$6.00	25	45

Table 6-8. Estimated Producible Shale Gas in the Appalachian Basin (Ref. 6-11)

TECHNOLOGY	POTENTIAL RESOURCES, TCF, AT PRICE, $/MMBTU(1)					
	$2.50	$3.50	$5.00	$7.00	$9.00	INFINITE
TRADITIONAL	3.3	8.5	11.4	14.9	16.6	25.3
CONVENTIONAL	7.3	14.5	19.5	23.5	27.0	37.4
ADVANCED	11.8	20.1	27.2	32.9	38.9	49.9

(1) 1979 DOLLARS, 10% RATE OF RETURN

shale wells. Hydraulic fracturing is typically more effective than wellbore shooting, but presents several problems. Limited experimental evidence indicates that advanced technology could double the improvement of conventional technology over traditional technology.

The estimates of Tables 6-7 and 6-8 fall in the same general range. Constraints on production include uncertainty about the resource size and extraction economics, and the lack of pipelines near the gas resource.

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6.1.2.3 Tight-Gas Reservoirs

Devonian shale gas is sometimes included in the same category as tight formations. However, this report uses the approach of Reference 6-11, whereby the tight-gas category is limited to the tight-sand formations found primarily in the western United States. The definition of tight gas basically covers NG found in low-permeability blanket or lenticular formations. Historically, production from most of these formations has not been economical, but the price incentives of the NGPA have enhanced the outlook for tight gas. In addition, introduction of massive hydraulic fracturing techniques has improved well production rates substantially. A fractured well in a tight-gas formation typically produces at a lower rate, but over a longer period, than a well in a conventional formation, and recovers a much lower percentage of the in-place gas.

Estimated United States tight-gas resources and recoverable quantities are given in Table 6-9. The total in-place gas estimate of 924 TCF is somewhat higher than the National Gas Survey estimate of 793 TCF (Ref. 6-10). The recoverable amount depends on technology and price, and the estimates in Table 6-9 indicate that recovery potential is about equally dependent on price increases and technology development.

For comparison, Table 6-10 presents the American Gas Association published estimates of recoverable tight-sands gas (Ref. 6-10). These estimates are substantially lower than those in Table 6-9, but there is insufficient discussion in Reference 6-10 to reconcile the differences.

Major uncertainties and production constraints in this area are (1) inadequate technology for characterizing the producing formations and guiding the stimulation techniques, (2) inability to determine fracture geometry, (3) limited availability of federal lands for tight-gas development, and (4) insufficient price incentives to justify drilling risks.

Table 6-9. Estimated Total and Recoverable Tight-Gas Resources (Ref. 6-11)

CATEGORY	ESTIMATED TIGHT GAS RESOURCES, TCF		
	APPRAISED (12 BASINS)	EXTRAPOLATED (101 BASINS)	TOTAL (113 BASINS)
TOTAL GAS IN PLACE	444	480	924
TOTAL RECOVERABLE			
BASE TECHNOLOGY(1)			
@$2.50/MCF	97	95	192
$5.00	165	200	365
$9.00	189	215	404
ADVANCED TECHNOLOGY(1)			
@$2.50/MCF	142	189	331
$5.00	231	272	503
$9.00	271	303	574
MAXIMUM	293	315	608

(1) ASSUMING 15 PERCENT RATE OF RETURN AND CONSTANT 1979 DOLLARS.

Table 6-10. Estimated Recoverable Tight-Sands Resources (Ref. 6-10)

MARKET PRICE, $/MCF (1979 DOLLARS)	ESTIMATED RECOVERABLE TIGHT SANDS GAS RESOURCES, TCF	
	EXISTING TECHNOLOGY	ADVANCED TECHNOLOGY
$3.12	30	100
$4.50	45	120
$6.00	60	150

6.1.2.4 Geopressured Brines

Geopressured brine reservoirs underlie a large portion of the northern Gulf of Mexico coastal region in a strip 200 to 300 miles wide. The water, trapped at higher than the normal hydrostatic pressure by both faulting and shale barriers, is believed to contain significant quantities of dissolved methane. The reservoirs are located in sedimentary deposits that are up to 50,000 feet thick, and the reservoirs themselves are typically 500 to 1000 feet thick. The geopressured zones begin about 5000 to 10,000 feet below the surface and probably average about 10,000 feet in overall depth (Ref. 6-10).

The resource base is apparently very large, and in-place gas estimates vary from 860 TCF to as high as 100,000 TCF. Estimates of ultimately recoverable resources in Reference 6-10 range from 42 to 2000 TCF. However, other studies arrive at more conservative estimates of recoverable quantities. For example, a study of the 11 best prospects concluded from extrapolation of those data that ultimate recovery would range from 0.25 to 0.5 TCF (Ref. 6-11). Another study of 20 specific onshore reservoirs indicated that a maximum of 7.6 TCF of methane and 12.6 quadrillion Btu (quads) of thermal energy may be producible from these reservoirs at costs ranging upward from $5 per thousand scf (Ref. 6-12).

Development of a geopressured brine reservoir would consist of (1) drilling deep wells, (2) producing the hot salt water by natural flow, (3) conversion of the geothermal energy to electricity (when economic), (4) separation of the methane from the water, (5) sale of the methane, and (6) disposal of the produced water. Spent brine disposal in shallow saline aquifers is currently feasible, but reinjection into the production reservoirs is not cost-effective at the present time.

The major uncertainties in geopressured brine development are (1) methane saturation level in the brine, (2) reservoir quality, continuity and recovery factor, (3) sand production, (4) corrosion and scale potential, and (5) brine disposal.

6.1.3 Coal

Fossil and renewable materials which can be converted to SNG are addressed in this and the following two subsections. Foremost among these resources is coal in all its variations. Coal is the compressed and altered residue of ancient plants which were subjected over a long period of time to bacterial action, heat, and pressure. The first product in the process is peat, followed in turn by lignite, subbituminous coal, and bituminous coal. Coal strata subjected to extreme conditions became anthracite, the coal with the highest fixed carbon content and heating value. Coal is often as much as one-third mineral matter, denoted as ash.

Nearly two-thirds of United States coal resources are classed as low sulfur, i.e., 1 percent or less. Nearly 20 percent has more than 3 percent sulfur. Western coal is typically low-sulfur subbituminous and lignite coals.

It has been customary to include in domestic coal resources only those anthracite and bituminous coal seams which are at least 14 inches thick, and lignite seams at least 30 inches thick. Table 6-11 gives a USGS estimate of the amount of in-place coal as of 1974. The USGS estimates that there is about an equal quantity of coal as yet undiscovered to a depth of 3000 feet. Using a 50 percent recovery factor for

Table 6-11. Identified United States Coal Resources (Ref. 6-5)

COAL TYPE	RESOURCES,(1) 10^9 SHORT TONS
ANTHRACITE	19.7
BITUMINOUS	747.3
SUBBITUMINOUS	485.8
LIGNITE	478.1
TOTAL	1,730.9

(1) UNITED STATES IDENTIFIED COAL RESOURCES AS OF 1/1/74.

underground mining, and subtracting the 4 billion tons of coal produced during the 1974-79 interval, the total recoverable coal to 3000 feet without regard to cost is almost 1800 billion tons (Ref. 6-5). Peat resources in the United States, excluding the permafrost areas, are about 120 billion tons. However, the peat resources are not as well defined as other fossil fuel resources (Ref. 6-10).

Coal reserves are the portion of the in-place resource which is in seams minable with current technology. Economically recoverable reserves are classed as proved reserves. The maximum depth considered is generally 1000 feet, but only about 200 feet for lignite. The Bureau of Mines estimated the coal reserve base as 438 billion tons as of 1976, of which 141 billion tons were potentially minable by surface methods. Assuming 50 percent is economically recoverable, there are approximately 219 billion tons of recoverable coal reserves in the United States, including Alaska. These reserves are equivalent to 800 billion barrels of oil and can be compared to the 61 billion barrels of recoverable oil and oil-equivalent gas reserves in the United States (Ref. 6-13).

Despite these impressive reserve figures, significant obstacles must be overcome to achieve more widespread use of coal. Among the problems are (1) mining and utilization in an environmentally acceptable manner, (2) providing an adequate transportation system to move the coal to domestic and export markets, and (3) ensuring adequate production capability to satisfy demand (Ref. 6-13).

6.1.4 Biomass

For purposes of this report, biomass includes only growing plant life. Other resources sometimes included in this category, such as municipal solid waste and animal residues, are separately reviewed. Biomass can be divided into terrestrial and aquatic plants, and the former subdivided into wood and crops, including grasses. Since the major thrust of this section is the production of SNG or methanol, this discussion will omit the sugar and starch crops that are more suited to ethanol production.

Inasmuch as biomass is a renewable energy source, production rates are the appropriate resource measure. Another characteristic of biomass is that it tends to be diffusely located, so that collection will be a significant cost item. Also, biomass production is often susceptible to the vagaries of weather, insect infestation, and plant disease.

Wood comprises the largest amount of biomass material, but only about 30 percent of the wood in commercial forest lands can be recovered economically. Mill residues constitute the cheapest, most readily available woody biomass, but these are already in great demand. Logging residues currently total over 100 million dry tons per year, but collection costs and the lack of efficient collection machinery are major impediments to wider recovery. The same difficulty applies to other potential sources such as surplus growth, annual tree mortality, and noncommercial timber on commercial forest lands (Ref. 6-14).

It has been estimated that at a cost of $25 per ton (constant 1977 dollars), about 80 million dry tons of wood and unused wood wastes could have been collected for conversion to SNG or methanol in 1980. In 1990, only 65 million dry tons might be obtained at that price, and in 2000 the quantity is projected to drop to just under 40 million dry tons. The corresponding methanol yields would be about 10, 8, and 5 billion gallons, respectively (Ref. 6-14). If the wood were converted to SNG rather than methanol, approximately 0.7, 0.6 and 0.35 TCF could be produced in 1980, 1990, and 2000, respectively.

These estimates are based upon current lumbering operations. A cultivated forest could become a major source of biomass, and yields on existing commercial forest lands could be increased. It is possible that either of these approaches could increase current yields by a factor of two or three (Ref. 6-13).

Another cellulose-type biomass resource is crop residue. Of the nearly 400 million tons generated annually in the United States, only about 20 percent could be considered a fuel feedstock. Residues can be removed only if soil quality is not diminished. Other problems include

large storage capacity requirements, increased demand for fertilizer, and year-to-year fluctuations in availability. The low residue density makes both collection and processing difficult and costly. Also, fall harvesting interferes with fall plowing, possibly leading to a decrease in production the following year (Ref. 6-14). Another possible source of biomass is marine growth, but costs are currently prohibitive and technical developments are needed in harvesting and conversion (Ref. 6-13).

Reference 6-15 estimates that 3.4 billion gallons of methanol per year could be produced during the 1990-2000 time period from crop residues. This corresponds to about 0.25 TCF of SNG. Of course, an alternative use of crop residues is direct combustion in boilers and furnaces.

6.1.5 Waste Resources

This category includes urban refuse, industrial waste, sewage, and animal manures. Urban refuse, also known as municipal solid waste (MSW), includes household and commercial waste but not industrial, agricultural, or sewage waste. It is about 75 percent organic with the remainder mainly composed of glass, metals, and plastics. As indicated in Table 6-12, about 60 percent of the total MSW generated is available in population centers of sufficient size to economically support an SNG or methanol production plant. From the available waste, 9.8 billion gallons of methanol in 1990 and 11.5 billion gallons in 2000 could be produced (Ref. 6-15). The corresponding quantities of SNG are 0.77 and 0.90 TCF, respectively.

Industrial waste is composed of a wide variety of materials. Some, such as food wastes, are more appropriately converted to ethanol, while cellulose or plastic constituents are satisfactory feedstocks for gasification to SNG or methanol. It has been estimated that 17.5 million tons of organic solids were collected in 1980 with a projected growth to at least 25 million tons by 2000 (Ref. 6-10). These quantities could theoretically produce 1.5 and 2 billion gallons of methanol, respectively, or 0.11 and 0.16 TCF of SNG.

Sewage is over 99 percent water. It has been estimated that 6.9 million dry tons of sewage sludge were generated within the United States in 1980, with 70 percent processed through anaerobic digesters (Ref. 6-14). Of the methane produced in the nearly 6000 digesters, approximately 75 percent is either used by the treatment plant or sold to

Table 6-12. Projected Total and Available Municipal Solid Waste Generation (Ref. 6-14)

YEAR	MUNICIPAL SOLID WASTE GENERATION, 10^6 TON/YR TOTAL (1)	AVAILABLE (2)
1975-76	143	94
1980	170	108
1985	198	115
1990	225	124
1995	232	136
2000	240	145

(1) BASED ON EPA DATA.
(2) GENERATED IN AREAS WITH GREATER THAN 200,000 POPULATION, ASSUMED NECESSARY TO SUPPORT AN SNG OR METHANOL PLANT.

nearby utility plants; the remaining 25 percent is generally flared. This unused methane amounts to 0.008 TCF per year, and if converted to methanol it would supply about 84 million gallons. By 2000, the projected quantities are 0.010 TCF of methane and 98 million gallons of methanol. The feasibility and cost effectiveness of converting unused methane from these plants to methanol are questionable. Most large treatment facilities already use most of the methane they generate, leaving only small, dispersed facilities as potential SNG or methanol producers (Ref. 6-14).

The last waste item to be discussed is animal manure. Collection for processing into methane is limited by economics to operations

where substantial numbers of animals are confined to a relatively small area. Only cattle in large feedlots generate sufficient manure to warrant selling the gas instead of using it on-site, and even then the economics are questionable. In most places, the digested solids, when sold as cattle feed or fertilizer, are more valuable than the gas. The resource potential of manure as a source of methane for vehicle use is therefore considered small on a national scale (Ref. 6-10).

6.2 PRODUCTION TECHNOLOGY

Some knowledge of the technology for production of NG, SNG, and methanol is necessary to properly assess these fuels. A review of the processing steps also includes the processing energy efficiencies used in Section 4 for evaluating the overall resource energy efficiency of transportation systems. However, to cover in sufficient depth the techniques for manufacture of NG, LNG, and methanol from the various fossil and renewable resources requires a very lengthy discussion. Therefore, the following material is included in this volume to summarize the most important subject areas, while a detailed review can be found in Volume III, Appendix C.

6.2.1 Natural Gas Processing, Transmission, and Storage

In the context of this section, production includes all the steps from extraction of the in-place natural resource to the initiating point for retail sales. For NG, the sequence proceeds from well drilling and field gathering through gas processing, compression, pipeline transmission, liquefaction if required, storage, and distribution. In 1980, over 175 thousand gas wells were in operation in the United States, and approximately one-quarter of the gas supply came from offshore wells (Ref. 6-17).

NG from a well usually contains over 85 percent methane by volume, with other hydrocarbons such as ethane, propane, butane, and some heavier molecules. In addition, the gas may contain varying amounts of water, sulfur compounds, carbon dioxide, nitrogen, and other impurities. In processing at the NG plant, most of the valuable butane and heavier

hydrocarbons, as well as a portion of the ethane and propane, are removed from the gas as natural gas liquids (NGL). The impurities are removed to meet specifications of state statutes or pipeline companies. Cryogenic processing is required if the remaining ethane is to be recovered, and at the same time, nitrogen can be removed to improve the heating value of the gas.

The NG from the processing plant is ready for compression and injection into the extensive national pipeline transmission system. Most major long-distance pipelines are more than 500 miles long, and a few exceed 1500 miles. Operating pressures are in the range of 700 to 1000 psi with some exceeding 1000 psi. Compressor stations are generally located every 50 to 100 miles. Fuel for the compressors is gas taken from the pipeline.

Storage facilities for NG have been developed in conjunction with long-distance pipelines in order that the system can operate at essentially a constant maximum throughput during the year. Excess gas available during the summer is stored for use during peak demands in the winter. Underground storage in depleted gas or oil reservoirs is the usual method. There are approximately 400 such storage reservoirs in 26 states at the present time.

Storage of gas in the form of LNG is an important technique to accommodate peak demands of up to a few days' duration. Such peak-shaving plants have liquefaction capacities ranging from 0.5 to about 20 million scf per day, with storage capacities between 100 and 300 times the daily liquefaction capability. LNG is attractive as a storage medium because 1 cubic foot is equivalent to approximately 630 scf of gas. However, it must be cooled to and stored at -260°F, requiring special equipment and the expenditure of about 14 percent of the gas energy content.

In the liquefaction process, gas constituents such as carbon dioxide (CO_2), hydrogen sulfide (H_2S), and water vapor (H_2O) must first be removed to prevent subsequent solidification. Maximum use is made of the compression energy of the pipeline feed gas, a particularly efficient

technique if gas must in any case be depressurized to distribution line pressure levels. The LNG can be moved from the liquefaction plant to satellite storage tanks by insulated tank trucks, railcars, or pipelines, the latter usually for relatively short distances.

6.2.2 Synthetic Natural Gas Production

Methane, the primary constituent of NG, can be manufactured from a variety of organic materials, ranging from solid fossil fuels to urban wastes. The largest potential source of SNG is coal gasification, but other resources may eventually make significant contributions, at least at the local level. In addition to gasification, microbial conversion of biomass and MSW to methane can be used and is generally preferred if the starting feedstock has a high water content.

The major steps in the production of high-Btu gas are coal preparation and pretreatment, gasification, shift conversion and cleanup, and methanation. Many processes have been developed around different gasifier designs. Inasmuch as coal is deficient in hydrogen (H_2), steam is usually introduced into the gasifier to supply supplemental H_2. The objective is to produce as much methane in the gasifer as possible, but the product gas will also contain some carbon monoxide (CO), CO_2, and H_2 in addition to H_2O and H_2S. The next step is to react some of the CO and H_2O to produce additional H_2 in the shift converter, after which the acid gases are removed. In the final step, the CO and H_2, now in the proper ratio, are converted in the methanator to additional methane and by-product water is removed. Construction of the first commercial methane plant based on coal has just been initiated in North Dakota.

Relatively dry renewable resources, such as wood and MSW, can be gasified in generally the same manner as coal. Aquatic plants, some terrestrial grasses, animal manures, and sewage are more amenable to anaerobic digestion for conversion to methane. The process directly produces a mixture of methane and CO_2 from which the latter can be easily removed. In addition to methane recovery during anaerobic digestion of

liquid wastes, there has been, in recent years, increasing production of methane from microbial action in sanitary landfills.

6.2.3 Methanol Production

Methanol can be synthesized from a gaseous mixture of CO and H_2, made from a wide variety of fossil and renewable resources. Although presently produced in the United States by reforming NG, the most promising source for the synthesis gas in the future is coal. The process differs from the production of SNG described previously in that the gasifier is operated at higher temperatures to minimize methane formation in favor of CO and H_2. The final step then uses conditions and catalysts that lead to methanol formation in place of methanation. The various synthesis processes differ primarily in the converter design and operating pressure. No commercial plants have been built as yet in the United States using coal as the feedstock.

Other relatively dry materials, such as wood and MSW, could be gasified to a synthesis gas but additional development and demonstration is required before a commercial-scale plant could be seriously considered. Reforming methane produced by anaerobic digestion is not economically attractive since there is usually a market for the methane, and the small-scale conversion to methanol would not be cost-effective.

6.2.4 Production Energy Efficiency

Supply chain efficiencies for each major step from resource extraction to the retail sales point are summarized in Table 6-13 for methane and in Table 6-14 for methanol. The total logistic chain efficiencies for these fuels, as well as for conventional fuels, are presented in Section 4, while a discussion of the assumptions and data sources for the table values can be found in Volume III, Appendix C.

6.3 SUPPLY PROJECTIONS

NG supply forecasts through 2000 have been published by many organizations, but methanol projections are more limited in number. A basic problem is that it is often difficult to make meaningful comparisons

Table 6-13. Efficiencies for CNG and LNG Production from Natural Gas, Coal, Wood, and MSW

RESOURCE	PRODUCTION STEP EFFICIENCY CNG	LNG
NATURAL GAS[1]		
EXTRACTION AND GATHERING	0.964	0.964
GAS PROCESSING[2]	0.968	0.968
PIPELINE TRANSPORT	0.95	0.95
GAS STORAGE [3]	0.996	NA
GAS DISTRIBUTION	0.993	NA
LIQUEFACTION	NA	0.86
COAL[4]		
SURFACE MINING	0.986	0.986
COAL PROCESSING	0.95	0.95
COAL CONVERSION	0.65	0.65
PIPELINE TRANSPORT	0.95	0.95
GAS STORAGE [3]	0.996	NA
GAS DISTRIBUTION	0.993	NA
LIQUEFACTION	NA	0.86
WOOD		
HARVESTING	0.978	0.978
LOCAL TRANSPORT	0.979	0.979
WOOD CONVERSION[5]	0.60	0.60
PIPELINE TRANSPORT	0.95	0.95
GAS STORAGE[3]	0.996	NA
GAS DISTRIBUTION	0.993	NA
LIQUEFACTION	NA	0.86
MUNICIPAL SOLID WASTE		
COLLECTION	0.97	0.97
PREPARATION/CONVERSION	0.50	0.50
GAS DISTRIBUTION	0.993	NA
LIQUEFACTION	NA	0.86

(1) TYPICAL OF DOMESTIC GAS PRODUCTION.
(2) NATURAL GAS LIQUIDS EXTRACTION PLANT.
(3) UNDERGROUND OR GAS HOLDERS.
(4) TYPICAL OF WESTERN COAL CONVERSION NEAR MINE.
(5) ASSUMES CONVERSION BY THERMAL GASIFICATION.

BEST DOCUMENT AVAILABLE

Table 6-14. Efficiencies for Methanol Production from Natural Gas, Coal, Wood, and MSW

RESOURCE	PRODUCTION STEP EFFICIENCY
NATURAL GAS	
EXTRACTION AND GATHERING	0.964
PROCESSING	0.968
STEAM REFORMING AND SYNTHESIS	0.64
RAIL TRANSPORT(1)	0.98
COAL	
SURFACE MINING	0.986
COAL PROCESSING	0.95
COAL CONVERSION	0.62
RAIL TRANSPORT(2)	0.98
WOOD	
HARVESTING	0.978
LOCAL TRANSPORT	0.979
WOOD CONVERSION	0.55
RAIL TRANSPORT(2)	0.98
MUNICIPAL SOLID WASTE	
COLLECTION	0.97
PROCESSING AND THERMAL CONVERSION(3)	0.40

(1) BASED ON METHANOL SHIPMENT TO CHICAGO AREA FROM GULF COAST PLANT.
(2) BASED ON METHANOL SHIPMENT TO CHICAGO AREA FROM WESTERN U.S.
(3) ASSUMES LOCAL USE OF METHANOL PRODUCTION.

of different projections. For example, most gas forecasts include the following categories, but category definitions are not always consistent: (1) conventional NG, sometimes including Alaskan gas, (2) Alaskan gas, (3) unconventional NG, (4) SNG, which may be limited to gas from naphtha and

NGL, or also include gas from coal, peat, biomass, and waste, and (5) imported gas by pipeline from Canada and Mexico and by ship as LNG. In some cases onshore and offshore production are specified. Also, SNG often includes both high- and medium-Btu gas without distinction. Finally, the projections often are not made for the same years. Therefore, relatively few forecasts are included in this subsection, but they appear to span the range typically reported in the literature.

Demand and restrictions on demand by government regulations are among the many factors that may be included in a supply analysis. The general subject of NG demand is not separately addressed here, but the extent to which it is considered in specific supply projections is stated.

6.3.1 Natural Gas Supplies

Two major gas supply forecasts published within the past year form the cornerstone of this subsection. The one by DOE is documented in Reference 6-13, and the other by the American Gas Association (AGA) is described in Reference 6-10. Although selected primarily as authoritative sources, they also provide the low and high extremes of gas supply projections. The breakdown of future gas sources for each of these forecasts is shown in Table 6-15. Since the AGA forecast is for 1990 and 2000, comparisons could only be made for these two years.

It is apparent from the table that there is a significant difference in the two forecasts, with the DOE values considerably lower than those of AGA. Part of the disparity results from the fact that the former is demand constrained, while the latter is not. DOE, in its 1980 Annual Report to Congress, forecasts lower demand for NG due to (1) conservation resulting from price increases, (2) restrictions on use, such as the Powerplant and Industrial Fuel Use Act of 1978, and (3) increasing use of low- and medium-Btu gas from coal in central power generation and in industry. The DOE in its forecast states that more gas could be produced if needed. Additional discussion of the two forecasts is presented below, starting with that from DOE, to aid in understanding the rationale for the projections.

Table 6-15. Projections of U.S. Gas Supply from All Sources

SOURCE	PROJECTED U.S. GAS SUPPLY, TCF				
	1985	1990		2000	
	DOE(1)	DOE(1)	AGA(2)	DOE(1)	AGA(2)
DOMESTIC PRODUCTION					
CONVENTIONAL					
LOWER 48 STATES	15.8	13.3	15-17	10.4	12-14
ALASKA	0.0	0.9	0.8	1.3	1.5
ENHANCED RECOVERY	0.7	1.3	0.4-1.0	4.6	1.5-3.0
SNG FROM COAL	0.1	0.1	1.0	0.3	1.5-2.5
GAS FROM NAPHTHA, NGL	0.0	0.0	0.3	0.0	0.3
OTHER	0.0	0.0	0.2-0.6	0.0	1.0-2.5
SUBTOTAL	16.6	15.6	17.7-20.7	16.6	17.8-23.8
NET IMPORTS					
CANADIAN PIPELINES	0.6	0.1	1.7	0.0	2.0
MEXICAN PIPELINES	0.1	0.1	1.0	0.0	2.0
LNG SHIPS	0.8	0.8	1.5	0.6	2.5
SUBTOTAL	1.5	1.0	4.2	0.6	6.5
TOTAL SUPPLY	18.1	16.6	21.9-24.9	17.2	24.3-30.3

(1) DOE Annual Report to Congress, 1980; Mid Case Scenario, (ref. 6-13).
(2) The Gas Energy Supply Outlook: 1980-2000, AGA; moderate import scenario (ref. 6-10).

6.3.1.1 DOE Forecast

The DOE analysis is keyed to the price of oil. An analysis of the world oil market leads to three scenarios about future international oil prices. Based on the price assumptions, projections are provided for both world and domestic energy markets. The forecasts in Table 6-15 are for the "middle" oil price scenario in which 1985, 1990 and 2000 oil prices (in 1979 dollars) are $37, $41 and $60 per barrel, respectively. The analysis assumes that production of conventional gas continues to exceed the rate of reserve additions, although the gap between the two narrows. Consequently, conventional reserves continue to decline and pro-

duction declines as well. Declines in conventional lower 48 states NG production are offset entirely by increased production from new sources, particularly gas from tight formations. As a result, total annual domestic gas production in 2000 is projected to be the same as in 1985.

The DOE projections assume that the Alaskan Natural Gas Transportation System (ANGTS) will not be ready for operation until shortly after 1985, but that demand at that time will be sufficiently strong for the full initial pipeline capacity of 2.4 billion scf per day to be used. Production of gas from two unconventional sources, western tight sands and eastern Devonian shale, is forecasted to grow, mostly from current proved reserves. About twice as much could be produced from these sources, but it is assumed that gas prices continue to lag oil prices and adversely affect development until almost the turn of the century. For a similar reason, commercial production from other unconventional sources, including biomass and waste, is not included in the projections. Production of high-Btu coal gas from two demonstration plants is included in the 1990 DOE forecast, with modest growth to 2000. The analysis assumes that the demand for high-Btu gas starts to decline after 1990 for the reasons given in the preceding subsection. Synthetic gas is not forecasted to be manufactured from petroleum naphtha, LPG, or NGL due to unfavorable economics.

The import situation is highly uncertain. The DOE expects pipeline NG imported from Canada to decline from present levels of near 1 TCF per year to about a tenth of that in 1990, with a complete phase-out by 2000. A similar situation exists with Mexico, where a current agreement covers the importation of 0.1 TCF per year, now at the same price as Canadian NG. With the clouded political and economic picture, DOE sees only a decline in pipeline imports despite probable gas availability.

The LNG picture is not too different. The original contract in 1969 called for an LNG price of $0.305 per thousand cubic feet (Mcf) from Algeria. Several price increases were forced upon El Paso Co., the principal importer, culminating in a demand for $6.11/Mcf f.o.b.

Algeria. With transportation and processing, the delivered price would have risen to about $8/Mcf. Algeria stopped shipments in April 1980. The U.S. government, bargaining on behalf of El Paso, refused to pay the increase and broke off negotiations in February 1981. Shortly thereafter, El Paso announced it was discontinuing its LNG business in view of the remote prospects for resumption of the project (Ref. 6-18). The three East Coast utilities that were to receive the Algerian gas are still working with the Algerians on a new deal (Ref. 6-19). The DOE forecast assumes only currently contracted amounts are imported and these start phasing out in the 1990s.

The DOE total supply projection calls for a continuing slow decline in the overall gas supply from about 20 TCF in 1978 (not shown in Table 6-15) to 17.2 TCF in 2000, about a 0.7 percent average annual rate of decline. However, total supply is expected to satisfy demand. It should be noted that the DOE forecast did not allow for any vehicular demand of NG, either as CNG, LNG, or methanol.

6.3.1.2 AGA Forecast

The AGA forecast for the 1980-2000 period was published in October 1980. Four supply scenarios are presented in Reference 6-10 to illustrate the impact of national policy on the production from a particular source of gas, although total gas supplies do not differ substantially between scenarios. The Moderate Imports Scenario was selected for this study since it is based on a prudent national policy of maintaining a broad mix of fuels from diverse sources.

In the case of conventional NG from the lower 48 states, the projections were adopted by the AGA Gas Supply Committee after consideration of (1) potential gas resources and future reserve additions, (2) recent drilling activity and constraints to increased activity, (3) a survey of production estimates by 13 major gas producers and pipeline companies, and (4) evaluation of results of available gas forecasting models. With regard to NG supplies from Alaska, commercial sales within Alaska and for export to Japan as LNG began in the 1960s from Cook Inlet

in southern Alaska. Current net production in Alaska is about 0.2 TCF annually, of which about 0.03 TCF is used within the state, about 0.05 TCF is exported to Japan, and the remainder is used by producers. There is presently no commercial production from the North Slope, which contains 77 percent of the proved reserves, since no gas transportation system exists yet. The estimates of Alaskan production in Table 6-15 represent gas from the North Slope and LNG deliveries from southern Alaska, although the latter quantities amount to only 0.1 to 0.2 TCF per year.

The next item is enhanced recovery, specifically from tight formations. Gas is now being produced from western tight-gas sands at about 0.8 TCF per year and from eastern Devonian gas shales at about 0.1 TCF annually. Production forecasts for 1990 and 2000 are affected by both gas price and the status of technology. The projections shown in Table 6-15 do not include current production, which is included in conventional gas.

For high-Btu coal gasification, strong support for plant construction in the form of loan guarantees was assumed. As many as 15 full-scale plants could be under construction by 1990. Thereafter, an average of two to three commercial-scale facilities are estimated to go into construction annually, with total production by 2000 of as much as 2.5 TCF per year.

The AGA projection includes a small quantity of SNG produced from liquid hydrocarbons, such as naphtha and NGL. Only a few new plants are envisioned, and to be conservative AGA based its forecast only on existing facilities. The values in Table 6-15 are midway between the present operating level and the maximum available with year-round operation of all facilities. This would require some operational modifications of current seasonal plants.

The AGA forecast includes a catch-all domestic source category that covers gas from biomass, urban and livestock wastes, coal seams, in situ coal gasification, geopressured zones, peat, and oil shale. However,

the DOE projection considers that these sources make a minor contribution to the nation's gas supply.

With regard to pipeline imports from Canada, the values shown in Table 6-15 assume a Canadian policy to fully develop the frontier areas and to expand exports to the United States. Mexican gas imports currently run at a rate of 0.1 TCF per year with a price of $4.47 per million Btu. With proven reserves estimated at 64 TCF and additional gas resources that may be as high as 400 TCF, it is clear that Mexico could produce and export large quantities of gas. The amount available for export to the United States will be determined by three factors: (1) the results of Mexico's domestic program to increase NG consumption, (2) policy considerations relating to the inflationary effects of large amounts of dollars entering the economy, and (3) agreements setting the allowable price and volume of United States imports. In view of the production capabiliity and economic benefits of exporting gas to the United States, the AGA estimated a relatively high availability of such gas.

While the foreign resource base is sufficient to support significant LNG exports to the United States, actual availability is restricted. Some countries may wish to develop alternative uses, such as petrochemical feedstocks. Other foreign markets will compete with the United States for available supplies. The high capital costs of liquefaction facilities, and a policy of pricing at crude oil equivalence, may force the delivered price beyond an acceptable level. The AGA forecast is based on several new LNG export projects announced by foreign governments, and assumes the support of United States regulatory agencies.

The major conclusion was that sufficient gas will be available in the year 2000 to continue the supply of at least 25 percent of the nation's total need for energy, and possibly as much as 33 percent - the level provided by gas during the late 1960s and early 1970s. Conventional lower 48 states production is presently the nation's most important source of NG and will continue to be for the remainder of the century. Pipeline deliveries from Alaska, Canada, and Mexico will be the predominant

supplemental supply sources during the 1980s. Domestic gas resources which require technological advances for economic development will be of prime importance during the final decade of the century.

6.3.1.3 Comparison of Gas Supply Projections

In this subsection, the DOE and AGA forecasts and other recent projections are compared. First of all, the AGA estimates in Table 6-15 substantially exceed those by DOE in all categories except Alaskan gas and enhanced recovery. The greatest source of difference is the import forecast. DOE estimates of domestic gas production are within 1 to 2 TCF of the AGA lower bound for both 1990 and 2000, but because of the import difference, the total supply quantities differ by 5 to 7 TCF.

In Reference 6-13, DOE compared several NG supply forecasts for 1990, including its current and previous (1979) projection (see Table 6-16). According to DOE, the supply curves used for its latest forecast are less optimistic than last year's curves. Revisions in the reserve base and lower assumed finding rates lead to lower projected gas production in the 1980 forecast than in the 1979 forecast at the same gas price. The projected supply is also somewhat smaller due to constrained demand, which dampens price increases for gas at the wellhead. The 1980 forecast for conventional production, which includes some nonconventional sources, is the lowest of all the projections shown. The decrease in conventional gas between the 1979 and 1980 reports is also reflected in the 3 quad drop in total supply. However, the 1980 Annual Report total supply is not far below the Shell and Exxon projections. Conversely, the AGA forecasts are the highest of all the sources presented. A forecast by the Gas Research Institute (GRI), given in Reference 6-20 but not shown in Table 6-16, approximates the AGA values.

The most likely gas supply values appear to lie between the 17.2 TCF projected by DOE for 2000 and the 24.3 TCF at the lower end of the range estimated by the AGA. According to Tenneco Oil Company, the supply level until the end of the century will not depart significantly

Table 6-16. Comparison of 1990 Forecasts of U.S. Gas Supply (Ref. 6-13)

SOURCE	PROJECTED 1990 U.S. GAS SUPPLY, Quads						
	DOE FORECAST						
	1979 ANNUAL (1)	1980 ANNUAL (1)	1980 PNE (2)	AGA (3)	DRI (4)	EXXON (5)	SHELL (6)
DOMESTIC PRODUCTION							
CONVENTIONAL							
LOWER 48 STATES	17.8	14.7 (7)	16.7	15.5-17.3	16.6	15.7	14.5
ALASKA	0.9	0.8	1.3	0.8	0.4	NA	0.8
SNG & ENHANCED RECOVERY	0.3	0.9	0.4	1.9-3.0	0.5	NA	1.0
SUBTOTAL	19.0	15.9	18.4	18.0-21.1	17.5	15.7	16.1
NET IMPORTS							
PIPELINE	0.0	0.2	NA	2.8	2.1	NA	0.6
LNG	0.8	0.8	NA	1.5	1.0	NA	0.7
SUBTOTAL	0.8	1.0	2.8	4.3	3.1	2.1	1.3
TOTAL SUPPLY	19.8	16.9	21.2	22.3-25.4	20.6	17.8	17.4

(1) MIDDLE SCENARIO FROM DOE ANNUAL REPORT TO CONGRESS.
(2) POLICY & EVALUATION. U.S. DEPARTMENT OF ENERGY. REDUCING U.S. OIL VULNERABILITY. NOVEMBER 1980 VALUES. CONVERTED AT 1025 BTU/SCF. ALL OTHERS AT 1020 BTU/SCF.
(3) AMERICAN GAS ASSOCIATION. MODERATE WORLD IMPORTS SCENARIO (REF. 6-10).
(4) DATA RESOURCES, INC., ENERGY REVIEW, AUTUMN 1980.
(5) EXXON COMPANY, USA. ENERGY OUTLOOK 1980 - 2010. DECEMBER 1980.
(6) SHELL OIL COMPANY. NATIONAL ENERGY OUTLOOK, NOVEMBER 1980.
(7) INCLUDES SOME NONCONVENTIONAL GAS.

from the current annual consumption of 20 TCF, although the sources of gas will change substantially during that time period (Ref. 6-21).

The results of an analysis presented in Section 5 indicate that the maximum petroleum displacement potential due to automotive fleet use of NG is about 17 billion gallons per year, corresponding to about 2 TCF of gas consumption annually. Assuming that a realistic rate of market penetration will lead to vehicle gas usage of less than 1 TCF per year, the supply system should be capable of accommodating the additional demand.

6.3.1.4 Effect of Early Price Decontrol

No discussion of projected NG supplies would be complete without some comments on the effects to date of the NGPA, and possible consequences of early price decontrol as advocated by many gas producers. However, it should be appreciated that, in light of the complex provisions of the current NGPA and the strong divergence of opinion on

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proposed decontrol modifications, a complete discussion of the subject is outside the scope of this study.

The present Act was drafted in 1978 after dwindling NG supplies in the United States caused critical shortages in 1976 and 1977. The industry argued that higher prices were needed to give producers an incentive to search for NG and to encourage conservation. In drafting the Act, Congress hoped to make the price of newly discovered NG (discovered after the spring of 1977) equal to the price of an equivalent amount of crude oil by 1985. It attempted to do this in stages to ease the blow to the consumer. The price of new gas was pegged at $1.75 per million Btu, and 10 percent annual price increases were allowed until 1985, when the controls were to be lifted completely. The schedule was based on the assumption that crude oil would cost $15 per barrel in 1985. The legislation also attempted to protect supplies for residential and commercial customers by forcing large industrial users to pay a premium price, the so-called incremental pricing provision. To further ensure that industrial customers did not siphon off too large a share of the premium fuel, Congress passed the Power Plant and Industrial Fuel Use Act of 1978, which prohibits the use of NG for industrial and utility power generation after 1990 (Ref. 6-22).

The results of these actions, plus crude oil decontrol, have been manifold. Gas well drilling increased by 33 percent between 1978 and 1980. Crude oil prices sprinted well past $15 a barrel, to more than twice that price, so that NG still costs significantly less (Ref. 6-22). Some gas in certain high-cost categories has been decontrolled already. This includes gas from wells deeper than 15,000 feet, and from coal seams, Devonian shale and geopressured brine. Although not decontrolled, gas from tight sands has an incentive price equal to twice the price of gas from new onshore production wells. However, while gas supplies have increased, and the industry consensus is that the NGPA is working much better than originally expected, a number of issues still concern various segments of the industry. The fact that opinions on some of the issues,

particularly early decontrol, vary with the individual or company's position in the gas business has added to the controversy.

Just how high gas prices would go under decontrol is itself a center of controversy. One indicator is the price of deep gas (greater than 15,000 feet). It now sells for an average price of about $6 per million Btu (Ref. 6-22), and some uncontrolled deep gas reportedly has been sold at more than $8 per million Btu (Ref. 6-23). Distributors, transmission companies, and consumer groups believe that gas would rise as high as $7 per million Btu if all gas were suddenly decontrolled. By way of comparison, the average wellhead price in February 1981 was about $1.70 per million Btu (Ref. 6-24).

Producers argue that, with the new supplies decontrol would generate, the price of uncontrolled gas would probably settle near $4.50 per million Btu, about the price that the United States currently pays for imported NG from Canada and Mexico. A study conducted for the Natural Gas Supply Association arrived at a price in the $4 to $4.50 range for decontrolled gas (Ref. 6-25). The study concludes that only with substantial improvement in economic incentives for producers through decontrol will the United States even maintain supplies at the 1980 level.

The AGA takes an opposite stance. The AGA claims that decontrolled gas prices would double for all users, decreasing gas use by 10 percent (Ref. 6-26). The market for 1.6 TCF per year would be lost as a result of gas users switching to oil and 0.3 TCF per year would be lost to conservation. Oil imports would increase by 800,000 barrels per day and the inflation rate would rise from 9.2 to 12.6 percent annually. Losses in demand would reduce the incentive to invest money in the development of deep gas (Refs. 6-27, 6-28).

Secondary effects of decontrol also elicit diverse responses. As an example, a representative of Celanese Chemical Co. asserted that if NG is decontrolled, more people will move in the direction of coal. With a rise in gas prices, coal gasification will become commercially competitive. Conversely, a representative of Chem Systems, Inc. sees decontrol

as limiting SNG activity, since domestic supplies of NG would increase with higher prices. There does seem to be general agreement that higher NG prices as a result of decontrol will reduce the ability of U.S. petrochemical firms to compete on world markets. This has been experienced in the case of oil decontrol and already to a limited extent for gas feedstocks. Mexican and Canadian methanol capacity based on low-cost gas is growing, and the import of increasing quantities of methanol can be foreseen (Ref. 6-28).

6.3.2 Methanol Supply Forecast

Unlike the situation for NG, estimates of future methanol supplies are fewer and more restricted in time span. In addition, current methanol projections place more emphasis on the demand side, with less detail on supply sources. The discussion here focuses on some of the recent projections in the literature with their points of similarity and difference.

A forecast by Chem Systems, Inc., is summarized in Table 6-17 for 1990 and 2000 (Ref. 6-29). However, there is considerable disagreement among forecasters on the supply and demand future for methanol, both for the United States and on a worldwide level. One reason is that both the traditional sources of methanol and its markets are changing rapidly. Coal is already the focus of several studies as a new source of supply, while a host of developing applications will take up an increasing share of the methanol output.

Although methanol experts question whether direct application as an automotive fuel or as methyl tertiary butyl ether (MTBE) will constitute as large a portion of demand as Chem Systems has assumed, there appears to be little disagreement that demand will rise substantially around the world. There appears to be more disagreement about supply, with Chem Systems predicting a shortage by 1990, while British Sulphur Corporation sees a surplus of 135 million gallons per year worldwide by 1985 (Ref. 6-30).

Table 6-17. Projected Methanol Demand and Supply in the United States and the World

CATEGORY	PROJECTED METHANOL DEMAND/SUPPLY, 10^6 gal/yr[1] 1980 WORLD	1980 U.S.	1990 WORLD	1990 U.S.	2000 WORLD	2000 U.S.
DEMAND						
CURRENT USES (CHEMICALS, SOLVENTS)	NA	960	NA	1770	NA	< 2610
DEVELOPING APPLICATIONS[2]	NA	110	NA	1040	NA	≥ 2610
TOTAL	4020	1070	9370	2810	17400	5220
SUPPLY						
PRODUCTION (FROM NG AND PETROLEUM)	4020	1060	9370	1810	NA	NA
NET IMPORTS[3]	0	10	0	1000	NA	NA
TOTAL	4020	1070	9370	2810	NA	NA

(1) Based on data from Chem Systems, Inc., 1981 (Ref. 6-29).
(2) Fuel and fuel additives, single cell proteins, acetic acid.
(3) Shortfall may be supplied in whole or in part from coal.

If the Chem Systems demand estimates are reasonably correct for the United States, this country will have to increase its production and/or its imports substantially. If NG is decontrolled in the near future, it will lose its attractiveness as a methanol feedstock and greater emphasis will be placed on coal as the raw material. Coal plants tend to be very large facilities, and two production units of 40,000 to 50,000 barrels per day capacity would be adequate to satisfy the estimated domestic shortfall in 1990. However, considering the long construction lead times required for such plants, it is probable that methanol imports to meet traditional demands and automotive fuel requirements would have to increase substantially at least into the 1990s, thus substituting foreign methanol dependence for petroleum dependence. In any case, conversion of all SI large-fleet vehicles to methanol use would require over 15 billion gallons per year of methanol by 1985; this far exceeds the present and projected supply.

6.4 PROJECTED FUEL PRICES

Estimates of future fuel prices through 2000 are presented in this subsection. The fuels considered include gasoline and distillate fuel for reference, with CNG, LNG, and methanol the alternatives of

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interest here. Most of the projected prices are based on the use of NG and petroleum as feedstocks, but some estimates of methanol and SNG derived from coal, wood, and MSW are included.

It should be noted that these price forecasts are approximate and highly uncertain. In addition to the uncertainty in predicting future resource and production costs, there is the inherent difficulty of choosing one set of values to represent all the possible variations in resource properties, process technologies, plant sizes and locations, and economic assumptions. Consequently, the projections presented here are only generally indicative of the price structure and relative values of the fuels.

In Table 6-18, product demand prices are those paid by consumers at the utilization end of the logistic chain. Except as indicated, the data are from the 1980 DOE Annual Report to Congress (Ref. 6-13), adjusted to constant 1980 dollars. In the case of NG and its derived fuels, less than 2 percent in the year 2000 represents SNG from coal, according to DOE projections. The CNG and LNG compression and liquefaction costs were taken from AGA data in Reference 6-31. Methanol manufacturing costs based on NG were assumed to remain the same as current values (in constant 1980 dollars) except for small increases due to changes in NG costs.

When available cost data for methanol and SNG from other resources were examined, it was evident that there was great variability in the economic assumptions and methods of calculation. In order to provide a common cost calculation approach, National Gas Survey equations recommended by Skamser (Ref. 6-32) were used for all the synthetic fuel calculations. The equation for average gas cost over the plant life, using utility financing and assuming a 20-year plant life, 5 percent straight-line depreciation and 48 percent federal income tax, is given by:

$$\$/10^6 \text{ Btu} = \frac{N + 0.05\,(C-W) + 0.005\,\left[p + \frac{48}{52}\,(1 - d)r\right]\,(C + W)}{G} \qquad \text{(Eq. 6-1)}$$

Table 6-18. U.S. Energy Prices: History and Projections (Ref. 6-13)

SOURCE/FUEL TYPE	U.S. ENERGY PRICES, 1980 DOLLARS[1] 1981	1985	1990	2000
SUPPLY PRICES				
OIL, DOLLARS PER BBL				
DOMESTIC WELLHEAD AVERAGE	29.55	40.44	44.55	NA
IMPORTED AVERAGE	33.99	40.96	45.33	NA
NATURAL GAS, DOLLARS PER MCF				
DOMESTIC WELLHEAD AVERAGE	1.60	3.58	3.76	NA
IMPORTED AVERAGE	4.07	6.65	7.17	NA
COAL, MINEMOUTH, DOLLARS PER TON[2]	26.99	31.70	33.40	NA
DEMAND PRICES, DOLLARS PER EQUIV. GAL_E[3]				
DISTILLATE[4]	0.67	1.04	1.16	1.91
GASOLINE[5]	1.08	1.51	1.60	2.35[6]
NATURAL GAS[7]	0.42	0.67	0.72	0.79
CNG				
FROM NATURAL GAS[8]	0.65	0.90	0.95	1.02
FROM COAL[9]	-	1.05	1.09	1.13
LNG				
FROM NATURAL GAS[10]	0.68	0.93	0.98	1.05
FROM COAL[9]	-	1.08	1.13	1.17
METHANOL				
FROM NATURAL GAS[11]	1.71	1.93	1.95	2.04
FROM COAL[9]	-	1.20	1.26	1.30

(1) Fuel prices from DOE's 1980 Annual Report to Congress (March 1981) converted to 1980 dollars, unless otherwise noted.
(2) National average.
(3) Energy-equivalent gasoline gallons, based on 125,000 Btu (HHV) per gallon of gasoline.
(4) Exclusive of taxes of $0.13/$GAL_E$.
(5) Exclusive of taxes of $0.15/$GAL_E$.
(6) Estimated from data in DOE's 1980 Annual Report to Congress (March 1981).
(7) Commercial prices.
(8) Price is sum of commercial NG price and AGA compression cost estimate of $0.23/$GAL_E$.
(9) Prices based upon DOE-projected coal prices and general gas cost equation for utility (CNG and LNG) or Private Investor (methanol) financing derived by national gas survey of the Federal Power Commission. Compression or liquefaction costs from AGA estimates. Prices do not include distribution markup.
(10) Price is sum of commercial NG price and AGA liquefaction cost estimate of $0.26/$GAL_E$.
(11) Price based on raw material NG price.

where

C = total capital requirement, 10^6 dollars

W = working capital, 10^6 dollars

N = total net operating cost in first year, 10^6 dollars

G = annual gas production, 10^{12} Btu per year

d = debt fraction

r = return on equity, percent per year

p = return on rate base, percent per year

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For private investor financing, the cost equation based on a 20-year plant life, 16 year sum-of-the-years'-digits depreciation, 100 percent equity capital, 12 percent discounted cash flow (DCF), and 48 percent federal income tax, is given by:

$$\$/10^6 \text{ Btu} = \frac{N + 0.247\ I + 0.1337\ S + 0.2305\ W}{G} \qquad \text{(Eq. 6-2)}$$

where

I = total plant investment, 10^6 dollars

S = start-up costs, 10^6 dollars

and the other symbols are defined the same as for utility financing.

The necessary capital and operating cost inputs to Skamser's equations were taken from various published estimates; a single source for all the fuel/resource combinations would have provided additional commonality but was not found. While the cost calculating technique used here is neither totally rigorous nor up-to-date, it is rapid in application and widely referred to in the literature.

The results of the synthetic fuels calculations based on coal are also shown in Table 6-18. Computed fuel costs are averages over plant life rather than first year costs. Methanol plants are assumed to be privately financed, while SNG plants are utility financed. The national average price advantage of CNG and LNG over gasoline (including taxes), which amounted to approximately $0.64 and $0.61 respectively (1981 dollars) per equivalent gallon in 1981 is forcasted to remain relatively constant through the 1980s and then increase significantly as petroleum prices rise rapidly. The price of CNG and LNG manufactured from coal is projected to be about 11 to 17 percent higher than CNG and LNG based on NG. This is consistent with published reports projecting near price parity of SNG from coal with NG in the 1990s (Ref. 6-33). Methanol now has a price disadvantage (including taxes) of about $0.53 (1981 dollars) per equivalent gallon. Conversely, the price of methanol from coal is expected to be about 35 to 38 percent lower than methanol produced from NG

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and, indeed, lower than the price of gasoline, consistent with other forecasts (Refs. 6-34 and 6-35). These generally favorable projections are the result of both the predicted lower cost of coal and the very large production plants assumed to be built for these conversion processes. This would result in a price advantage over gasoline in 1985 (including taxes) of about $0.51 (1981 dollars) per equivalent gallon. It should be noted, however, that none of these coal conversion facilities has been built in the United States as yet, and thus the projected SNG and methanol prices remain to be confirmed.

It is not possible to present similar fuel price data based on wood and MSW resources inasmuch as raw material costs (wood) or credits (MSW) as a function of time were not found in the literature. However, using a cost of $20 per ton for wood (Ref. 6-36) and a credit of $5 per ton for MSW (Ref. 6-37), estimated prices of CNG, LNG, and methanol from wood and MSW were computed, as shown in Table 6-19. Comparison of these

Table 6-19. Projected Prices of Fuels Produced from Wood and MSW

FUEL	RESOURCE	FUEL PRICE $/10^6 BTU(1)
CNG(2)	WOOD	$ 9.50
	MSW	11.98
LNG(2)	WOOD	9.83
	MSW	12.31
METHANOL(3)	WOOD	12.40
	MSW	21.72

(1) BASED ON HHV AND 1980 DOLLARS.
(2) BASED ON REGULATED UTILITY FINANCING; INCLUDES $1.00 PER 10^6 BTU FOR PIPELINE DELIVERY (1000 MILES).
(3) BASED ON NONREGULATED PRIVATE FINANCING; INCLUDES $1.37 PER 10^6 BTU FOR RAIL DELIVERY (1000 MILES).

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prices with those in Table 6-18 indicates, with one exception, that use of wood and MSW results in the highest priced fuels. The only anomaly is the value for methanol from wood, indicated as being even lower than the current price from NG. It appears that either plant costs or the cost of wood may have been underestimated in the source used for these calculations.

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SECTION 7

VEHICLE SAFETY

To address the safety concerns associated with the use of methane-related highway vehicle fuels, the available safety information for natural gas (NG)- and methanol-fueled vehicles is examined in this section. The assessment begins with a review of the literature on NG vehicle safety, presented in Subsection 7.1. In Subsection 7.2, relevant data on the physical, chemical, and toxicological properties of NG and methanol are summarized, and compared with data for other common or proposed automotive fuels. Based on these properties, a preliminary comparison of potential design- and operation-independent fuel hazards is performed.

The potential hazards of NG fuel systems in normal operation are addressed in Subsection 7.3, major safety issues are identified, and the technology for hazard control is evaluated. Subsection 7.4 deals with fuel system hazards in accidents. Potential hazards are identified, and hazard control measures are evaluated.

Based on this assessment, there appear to be no fundamental barriers which would preclude the safe use of compressed natural gas (CNG) or liquefied natural gas (LNG) in highway vehicles. However, the available information on NG vehicles is limited and is not an adequate basis for final conclusions regarding the safety of NG fuel use in highway vehicles. Consequently, there are a number of areas in which additional information on NG system safety is needed, and several safety concerns remain unresolved, as discussed in Section 9.

The excellent safety record of CNG vehicles in Italy supports the finding that there is no inherent barrier to safe operation of highway vehicles on CNG fuel. However, the approaches to the use of cylinder safety devices, and the administrative procedures regarding CNG vehicles and equipment, differ considerably between the United States and Italy.

Consequently, extrapolation of the Italian CNG experience to the United States may be inappropriate in many respects. Although data have been amassed on the safety of NG vehicles in the United States, the accumulated mileage with such vehicles operating on NG is too limited for use in quantitative safety comparisons with conventional fuels, particularly in the crucial area of fire safety.

Although the fuel system hazards of gasoline and diesel vehicles are well recognized, an exhaustive comparison of the safety characteristics of conventional and NG-fueled vehicles is beyond the scope of this study. In general, NG either substitutes new concerns in single-fuel systems, or adds a second set of hazards in dual-fuel systems.

7.1 METHANE VEHICLE SAFETY LITERATURE REVIEW

7.1.1 Impact Tests

Highway vehicle impact safety with gaseous fuel systems was examined in a series of impact tests conducted in 1971 by Dynamic Science for the U.S. Department of Transportation (DOT), including barrier tests, cylinder drop tests, and sled tests (Ref. 7-1). The impact testing used full-scale vehicles and fuel system components to determine potential hazards resulting from fuel line rupture and tank retention failure. The fuel systems considered in this program were all of the dual-fuel type.

Five full-scale fixed barrier tests were conducted on CNG vehicles. The gas cylinders were pressurized with nitrogen at 2000 psi. Table 7-1 summarizes the test conditions and the peak longitudinal accelerations measured at the CNG cylinder racks (Ref. 7-1). Of particular interest are the results of a series of three impact tests conducted on 1965 Plymouth Belvedere sedans. These vehicles used six adjacent, coplanar, 25-inch-long high-pressure cylinders trunk-mounted parallel to the vehicle longitudinal axis. All cylinders were connected to a common manifold, from which a high-pressure fuel line led to the engine compartment. A high-pressure fuel shutoff solenoid valve was installed in the trunk between the manifold and the fuel line, in addition to a low-pressure solenoid valve located between the two pressure regulators in the engine

Table 7-1. Peak Acceleration during Dual-Fuel Vehicle Safety Impact Tests (Ref. 7-1)

VEHICLE	FUEL STORAGE CONFIGURATION	IMPACT		PEAK ACCELERATION AT CYLINDER RACK, G'S	
		TYPE	SPEED, MPH	IMPACT	RECOIL
1965 PLYMOUTH BELVEDERE SEDAN	SIX ADJACENT, COPLANAR 25 in. LONG CYLINDERS ALIGNED WITH VEHICLE LONGITUDINAL AXIS.	FRONT	30.1	49	41
1965 PLYMOUTH BELVEDERE SEDAN	SAME AS ABOVE, WITH TRANSVERSE RESTRAINING MEMBER ADDED TO CYLINDER RACK.	FRONT	29.8	23	NA
1965 PLYMOUTH BELVEDERE SEDAN	SAME AS ABOVE.	REAR	20.8	NA	25
1959 CHEVROLET 1/2 TON PICKUP TRUCK	TWO 51 in. LONG CYLINDERS MOUNTED ONE ABOVE THE OTHER INSIDE THE FRONT OF THE CARGO BOX, TRANSVERSE TO VEHICLE AXIS.	FRONT	29.6	59	15
1960 INTERNATIONAL 1 1/2 TON STAKE TRUCK	TWO 51 in. LONG CYLINDERS ATTACHED TO UNDERSIDE OF STAKE BED, ONE ON EACH SIDE, ALIGNED WITH VEHICLE LONGITUDINAL AXIS.	FRONT	29.8	38	16

compartment. The high-pressure rear solenoid valve was designed to close at a 500 psi pressure differential, thereby acting as an excess-flow limiting device. It should be noted that, currently, such devices are not commonly employed in CNG conversions. Consequently, the fuel system integrity of current CNG conversions in impact situations cannot be established on the basis of these test results.

In the first 30 mph front impact test, the cylinders escaped the mounting racks and intruded into the passenger compartment. This was attributed to inadequate retention strap tension. Despite this failure, the rear solenoid valve prevented leakage from the cylinders. The gasoline tank retention system also failed in this barrier test, resulting in spillage of the tank contents. A cylinder restraining member was added, and the test was repeated on a second sedan without any failures. It should be noted that most current car and light truck conversions use transverse cylinder mounts. Longitudinal mounting is still common in truck conversions, however.

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The last of the three passenger car tests involved a 21 mph rear barrier impact. The resulting rear end crush of 13.4 inches was insufficient to damage the cylinders. For the configuration tested, it was estimated that a rear barrier impact of up to 27 mph could have been tolerated without jeopardizing rear seat occupants. This was further estimated to correspond to approximately a 40 mph impact by a vehicle of equal mass, with the struck vehicle initially at rest (Ref. 7-1).

Drop tests were performed to determine the pressure integrity of the gas cylinders and cylinder valves under high shock loads. Cylinders were dropped onto a steel plate covering a concrete pad. The drop height and cylinder orientations tested are summarized in Table 7-2 (Ref. 7-1). The cylinders and valves suffered only minor visual damage, with no resultant leakage from the cylinders.

Table 7-2. CNG Cylinder Drop Test Conditions (Ref. 7-1)

CYLINDER SPECIFICATIONS			TEST CONDITIONS			
			CYLINDER ORIENTATION PRIOR TO DROP			
LENGTH, IN	WEIGHT,(1) LB	END GEOMETRY	ANGLE	VALVE	DROP HEIGHT, FT	IMPACT SPEED,(2) MPH
51	125	CONVOLUTED DISK	30° FROM VERTICAL	UP	30	44
			VERTICAL	DOWN	10	17
25	33	ELLIPTICAL	VERTICAL	UP	30	44
			VERTICAL	DOWN	10	17

(1) INCLUDES CABLE HOLDING CLAMPS.
(2) THEORETICAL.

Sled tests were conducted to generate data for use in developing crashworthy tank retention systems for dual-fuel automobiles. A crashworthy system was defined as one which prevents any intrusion into the passenger compartment and maintains fuel system integrity so that no fuel leakage occurs. Six sled tests were performed on CNG systems and four were conducted on LNG systems, as shown in Table 7-3. An automobile

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Table 7-3. Component Sled Test Summary (Ref. 7-1)

TEST NO.	RETENTION SYSTEM	CAR	FLUID TYPE (1)	FLUID LOADING	TEST DIRECTION	TEST SPEED, MPH	PEAK ACCELERATION, g's SLED	PEAK ACCELERATION, g's BODY BUCK	PEAK ACCELERATION, g's RACK
E-1	PNEUMETRICS CNG/ GSA MOD	1967 COMET	GN_2	2,000 PSIG	FORWARD	30.4	49	65	NA
E-2	PALCO CNG/ GSA MOD	1968 REBEL	NONE	NONE	FORWARD	30.3	49	52	NA
E-3	PALCO CNG/ GSA MOD	1968 REBEL	GN_2	1,750 PSIG	REAR	30.1	47	55	NA
E-4	DUAL CYLINDER CNG/WEST COAST	1968 FAIRLANE	GN_2	1,800 PSIG	FORWARD	30.7	57	61	NA
E-5	DUAL CYLINDER CNG/EAST COAST	1966 FAIRLANE	GN_2	NA	FORWARD	30.7	65	66	NA
E-6	PALCO CNG/ PALCO MOD	1968 REBEL	NONE	NONE	FORWARD	30.7	59	58	NA
F-1	BRENCAR LNG	1966 FAIRLANE	LN_2	55 LB	FORWARD	30.8	41	52	51
F-2	BRENCAR LNG	1959 CHEVROLET 1/2 TON PICKUP	LN_2	55 LB	FORWARD	30.4	44	50	31
F-3	ESSEX LNG	1966 FAIRLANE	LN_2	55 LB	FORWARD	30.8	42	46	49
F-4	AMETEK/STRAZA	1966 FAIRLANE	LN_2	55 LB	FORWARD	30.4	NA	NA	NA

(1) G = GASEOUS, L = LIQUID, N_2 = NITROGEN.

body buck (a section cut from a scrapped automobile), attached to the sled, was the test fixture to which the gas cylinders or tanks were installed. Target longitudinal and vertical accelerations of each body buck were 40 g and 20 g, respectively. The body buck orientation was pitched downward approximately 11 degrees to achieve the target vertical acceleration of 20 g. Sled deceleration was controlled by a crushable paper honeycomb impact stack, backed by a concrete buttress. The paper honeycomb stack was tailored to deliver the target 40 g deceleration pulse. Nominal impact speed was 30 mph.

The fuel systems were charged with nitrogen to simulate a fuel load. For the CNG systems at the service pressure level, this resulted in a slightly higher fuel system weight than would occur in service. The LNG systems were only filled about halfway with liquid nitrogen, to approximately the correct weight.

In five of the ten sled tests, the retention systems prevented significant cylinder movement, although some permanent deformation of the racks was noted. Significant cylinder movement occurred in two of the CNG tests and two of the LNG tests. In addition, the pickup truck bed holding the LNG tank separated from the vehicle during the sled test.

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A number of recommendations were presented by Dynamic Science for improving the retention systems. These include (1) providing additional structural members for the cylinder racks, (2) increasing the number and strength of the vehicle attachment points, and (3) strengthening the cargo box attachment in affected pickup truck conversions. The possible effectiveness of these improvements cannot currently be assessed due to lack of pertinent data.

7.1.2 Risk Analysis of NG-Fueled Vehicles

A study performed by Arthur D. Little, Inc. (ADL) in 1972 for the Massachusetts Turnpike Authority examined some of the risks associated with operation of gaseous-fueled vehicles in the Boston harbor tunnels and on a connecting toll road (Ref. 7-2). A risk analysis was performed, based on the probability of fuel release resulting from an accident involving gaseous-fueled vehicles, including CNG and LNG vehicles. Other accident hazards were not addressed. In addition to analyzing accident probabilities, the study examined the personal injury effect and the potential tunnel or roadway damage associated with the ignition of fuel released in an accident. Also, industry design and safety codes and standards, as well as the DOT pressure vessel regulations deemed necessary to ensure safe operation, were addressed in the study report.

The consequences of a fire or fuel tank rupture in a vehicular tunnel as a result of fuel tank failure were examined separately for CNG and LNG. Fire damage was addressed using approximate calculations of combustion and exposure times. For example, with CNG it was estimated that, in the absence of ventilation, the hot combustion products from 300 standard cubic feet (scf) of NG would fill a 60-ft section of the tunnel. The likelihood of serious damage to an oncoming vehicle or injury to its occupants was deemed to be slight, based on a residence time in the combustion zone of only about 1 sec at a vehicle speed of 35 mph. However, this is not true for the situation mentioned elsewhere in the same study, involving "hazards to motorists trapped in the tunnel after an accident," and also does not consider the hazard to the occupants of the gaseous-

fueled vehicle itself. Furthermore, the study did not consider possible detonation of the methane-air mixture within the tunnel. This subject is addressed in Subsection 7.2.2.

Explosion-related personal injury and tunnel damage were examined in detail by calculating blast wave overpressures resulting from bursting of CNG and LNG tanks. Failure of the pressure relief device was assumed as the worst-case condition. Personal injury was estimated to occur at distances of up to 45 ft from an exploding 25-gallon LNG tank, and up to 140 ft from a 300 scf CNG cylinder. Consideration of the allowable transient overpressure led to the recommended maximum LNG tank capacity of 25 gallons. For a CNG cylinder of 100 scf, the smallest capacity examined, the analysis predicted a dynamic overpressure nearly three times the allowable value, and over four times for a 300 scf tank. The authors attributed these results to the relatively high storage pressure of CNG, and suggested more detailed analysis of this case.

The ADL report distinguished between what were termed "well designed conversion systems" and "poorly designed systems." Large-fleet conversions were characterized as generally well designed systems, which are typically also well maintained, and carefully operated. Among the features of a "well designed" system were (1) fuel tanks mounted either on tracks inside the frame rail, or within the trunk at least 2 ft from the rear bumper, (2) tank supports designed to withstand ±40 g forward and aft accelerations, and (3) excess-flow shutoff valves located within the fuel tank assembly, not on the fuel line. It was pointed out that the excess-flow shutoff valve is a very important feature of a gaseous fuel system, because it will allow only small quantities of fuel to escape when a fuel line is ruptured.

The report concluded that well designed conversion systems, with proper installation, inspection, and maintenance, appear to present no more risk than gasoline systems. However, poorly designed conversion systems greatly increase the risk, particularly in confined areas such as tunnels, and must be considered unacceptable. Furthermore, because of the

dangers inherent in poorly designed systems, it was deemed essential by ADL that safety standards and regulations for gaseous-fueled vehicles be developed and enforced. These regulations should cover safety features, acceptable equipment, installation, inspection, and maintenance.

7.1.3 Methane Accumulation in the Passenger Compartment

During a dual-fuel vehicle test program by the General Services Administration (GSA), there was one incident in which fuel apparently leaked into the car and ignited when the engine was started (Ref. 7-3). This prompted the GSA to sponsor an experimental program by the National Bureau of Standards (NBS) to assess the potential for such incidents with both hydrogen and methane fuels (Ref. 7-4). NBS concluded that roof and firewall vents were highly desirable in such vehicles, even if a barrier is installed to isolate the trunk from the passenger compartment. Gas dispersion appeared to occur mainly by buoyancy-induced flow, making the roof vents of prime importance.

Other recommendations stemming from this program are (1) the fuel system must be designed for fuel containment in collisions, (2) the trunk must be vented if the fuel tank is located there, (3) the fuel tank vent should exit at the far rear of the vehicle, (4) a trunk membrane should isolate the trunk and the passenger compartment, and (5) a combustible-gas sensor should be located in the passenger compartment at the highest point of the roof, whether vented or not. In addition, the NBS noted that current heating and air conditioning systems would not be capable of handling the increased loads imposed by large vents. Therefore, an alternative configuration was identified, with the fuel tanks located outside the body shell. In this case vents may be unnecessary, but a combustible-gas sensor is still recommended.

7.1.4 Natural Gas Vehicle Safety History

A preliminary analysis of the safety history of NG-fueled highway vehicles was prepared for the American Gas Association (AGA) in 1979, using fleet data collected over the 1970-1979 time period by three gas utilities and one taxicab company (Ref. 7-5). The fleets comprised

479 sedans, 1,984 light-duty trucks, and 203 medium- and heavy-duty trucks, and are identified in Table 7-4, along with the corresponding mileage totals for the light-duty vehicles. The Southern California Gas Company, which operates 83 percent of the light-duty vehicles reported in the survey, is a subsidiary of Pacific Lighting Corporation, as is Dual Fuel Systems, Incorporated, the principal domestic manufacturer of CNG systems. Of the remaining vehicles identified in Table 7-4, all except the 35 taxis were also operated by gas utilities (Ref. 7-5).

Table 7-4. Dual-Fuel Vehicle Fleets Surveyed (Ref. 7-5)

		NUMBER OF VEHICLES				MILEAGE		
OPERATOR	FUEL	TOTAL FLEET	SEDAN	LIGHT TRUCK	TOTAL LDV	TOTAL, 10^6 MI	NG FRACTION[2]	TOTAL NG, 10^6 MI
SO. CALIF. GAS CO.	CNG/ GASOLINE	2240	324	1713	2037	150.0	0.75	112.5
ATLANTA GAS LIGHT CO.	LNG/ GASOLINE	91	30	61[1]	91[1]	1.7	1.0	1.7
LACLEDE GAS CO. OF ST. LOUIS, MO.	CNG/ GASOLINE	300	90	210	300	10.0	0.8	8.0
YELLOW CAB CO.s OF REDWOOD CITY AND SAN MATEO, CALIF.	CNG/ GASOLINE	35	35	0	35	12.6	0.8	10.8
TOTAL/AVERAGE		2666	479	1984	2463	174.3	0.76	133.0

(1) INCLUDES THIRTY 1 1/2 TON TRUCKS.
(2) ESTIMATED FROM REFERENCE 7-5 DATA.

The total mileage of the vehicles investigated was about 175 million miles. The mileage driven on NG was not specified, although in the case of the Southern California Gas Company CNG fleet it was stated that the goal has been to operate such vehicles on CNG 75 percent of the time. According to AGA, accident data for the Southern California Gas Company CNG fleet have not been kept separately, and thus the AGA assumed that the accident frequency with CNG is the same as with conventional vehicles. Collisions involving Southern California Gas Company's CNG vehicles total 99 percent of the estimated 1360 collisions involving the vehicles surveyed. Therefore, the findings were weighted heavily by AGA's accident rate assumptions for this fleet. The accident rate for the dual-

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fuel fleet vehicles surveyed in Reference 7-5 was 8 collisions per million vehicle miles travelled (VMT). For comparison, the 1979 U.S. vehicle accident rate was approximately 12 accidents per million VMT (Ref. 7-6).

There were no reported collision-related failures or fires involving the NG systems, although several other incidents were reported in which the NG system was identified as the fire source. These fires were attributed to faulty installation of gasoline bypass piping and to venting system deficiencies.

The data concerning gasoline-fueled automobile accidents and fires indicate that these sample fleets have accumulated insufficient mileage on NG to support conclusions about fire safety. In particular, the AGA analysis noted that accident-related automobile fires occur only about once per 100 million VMT. For the vehicles surveyed, the NG total was approximately 133 million miles, and passenger cars represent less than 20 percent of these. Therefore, a larger sample of NG-fueled cars would be needed for a statistically valid fire safety comparison with gasoline cars (Refs. 7-7 through 7-10). This is consistent with the AGA's finding that a need exists to begin development of a safety data base for NG vehicles on a common basis with gasoline units (Ref. 7-5).

Other test data indicate that the safe operation with NG depends on the gas being free of corrosive components (Ref. 7-11). The adverse effects of hydrogen sulfide (H_2S) on CNG steel cylinders were demonstrated in the October 1977 explosion of an NG transport vehicle in Shrewsbury, Kentucky. The pressure vessel was a new DOT-3T steel cylinder, which had been in service for about one week. Based on a metallurgical evaluation and fracture analysis of the cylinder, performed by NBS at the request of DOT's Office of Hazardous Materials Regulation, the failure was attributed to the combination of high H_2S concentration in the NG and microzones of high-hardness steel near the inside cylinder wall. Up to 500 parts per million of H_2S was measured in NG samples taken from the wells (Ref. 7-11).

Subsequently, DOT prohibited compressed gas transport cylinders with a volume greater than 1000 gallons for NG service. Such cylinders are designed for use with pure gases, including methane, but not NG. The practice of transporting NG is considered by the DOT Materials Transportation Bureau to represent a potentially unsafe condition, because it has not been demonstrated that impurities which may be present in the gas would not affect the structure of the particular steel used in the manufacture of these cylinders (Ref. 7-12).

In order to transport NG by truck, shippers must now apply for an exemption from DOT regulations, which define methane as a nonliquefied gas which has a minimum purity of 98.0 percent methane and which is commercially free of corroding components. The exemptions which have been granted to date apply to NG with not more than 0.5 lb H_2O per million scf (MMscf), or more than 0.1 grain H_2S per 100 scf. These levels may not now be generally achieved in normally distributed NG, despite the interests of the pipeline transmission and distribution companies in the survival of their equipment. For example, one pipeline company's specification allows the delivered gas to contain up to 7 lb H_2O per MMscf, and up to 0.25 grain H_2S per 100 scf (Ref. 7-13). Contaminants are also present in SNG, as discussed in Volume III, Appendix C. In addition to gas purity requirements, the exemptions have required use of special DOT3AAX trailer tubes, constructed of 4130X steel and subject to stringent testing requirements.

Because vehicle CNG fuel cylinders are not now subject to DOT regulations, a potentially hazardous condition may exist. To date, the maximum allowable safe concentration ranges of H_2S and other contaminants in NG have not been determined, and the long-term effects of H_2S exposure on CNG steel cylinders are unresolved. Aluminum cylinders, or composite cylinders with an aluminum inner shell, represent another possible solution, as discussed in Section 2. While contaminant control appears to be achievable through the use of existing gas scrubber technologies, such as those discussed in Volume III, cleanup costs will increase the cost of the fuel. Analysis of the economics of gas cleanup and of gas purity requirements are beyond the scope of this assessment.

7.1.5 Italian CNG Vehicle Experience

A recent report funded by the New Zealand Liquid Fuels Trust Board provides a comprehensive survey of CNG vehicle use in Italy as of 1979 (Ref. 7-14). The safety record of CNG, particularly of CNG cylinders, was especially addressed. CNG has been used as an automotive fuel in Italy since the late 1930s and about 275,000 vehicles, mainly private, are presently operated on CNG. Representatives of a number of Italian organizations have stated that there has not been a single recorded accident resulting from faulty CNG systems, and that when CNG vehicles were involved in accidents, CNG component failures rarely occurred and never caused any deaths or injuries. They also indicated that cylinder failures due to internal corrosion did occur in the early years of CNG vehicle use, and that the use of a dry, noncorrosive gas has been accompanied by a significant decrease in the incidence of cylinder failure. The New Zealand report concluded that the basic requirements for safe operation of CNG-fueled vehicles depend upon component reliability, installation integrity, and periodic inspection (Ref. 7-14).

Manufacture of CNG cylinders to Italian specifications is monitored by an Italian state board. Quality assurance includes burst testing, and samples reportedly burst at over three times the rated operating pressure. The Italian Ministry of Transport does not require pressure relief devices on vehicle cylinders, and deems these devices unreliable and subject to leakage. Their judgement is based on the absence of any recorded vehicle explosion. Additional consideration of the Italian cylinder specifications, and a comparison with DOT regulations, is covered in Subsection 7.4.4.

All Italian CNG vehicles must be inspected and approved by the Ministry of Transport upon conversion, and inspected annually thereafter. Cylinders are tested every five years and retired after 30 years. Testing is performed by a state board, the CNG Cylinder Management Fund, which in effect is the owner of all CNG cylinders. The vehicle owner pays a fixed per-cylinder rental quarterly to the Fund. If a cylinder must be replaced

because it failed the safety test, this is done without charge to the motorist. This system, although judged cumbersome by the authors of the New Zealand report, has had the advantage that cylinder failures automatically come to the attention of the controlling authority. However, because the safety record of the vehicle cylinders in Italy is extremely good, this system is apparently being superseded by one in which the vehicle owner purchases the cylinders at the outset (Ref. 7-14).

7.2 HAZARDS BASED ON FUEL PROPERTIES

This section presents physical, chemical, and toxicological data for methane and methanol, along with data for other common or proposed automotive fuels including gasoline, diesel fuel, commercial liquified petroleum gas (LPG), and hydrogen. The latter has been the subject of a number of safety assessments (Refs. 7-4 and 7-15 through 7-17). These data are intended to provide a basis for comparing environmental, health, and safety features of the various fuels.

7.2.1 Physical Properties

Table 7-5 compares the physical properties of the fuels. Density is one property that affects safety (Ref. 7-25). Vapors or gases that are heavier than air tend to settle near the ground where they can form flammable mixtures. At their normal boiling point, all of the listed vapors are heavier than air. For LNG spills in excess of several cubic meters of liquid, the evolving vapor is sufficiently cold that the resulting vapor-air cloud density is higher than that of air at ambient temperature, hence the cloud persists longer than if it were naturally buoyant (Ref. 7-26). For LNG spills in the significantly smaller quantities representative of vehicle fuel tanks, the vapor quickly attains positive buoyancy while mixing with air (Ref. 7-27).

A number of conditions are found near an unignited LNG spill. Directly above the boiling liquid layer is a heavy, fuel-rich, nonflammable mixture which becomes more buoyant and less fuel-rich at its outer boundaries. Consequently, there exists a flammable zone within which the air-fuel ratio is neither too rich nor too lean to support

Table 7-5. Physical Properties of Fuels (Refs. 7-16, and 7-18 through 7-24)

PROPERTY	GASOLINE	No. 2 DIESEL	METHANE	METHANOL	LPG	HYDROGEN
NORMAL BOILING POINT (NBP), °F	80-440	325-650	-259	148	-50	-423
HEAT OF VAPORIZATION, BTU/LB	130-150	70-155	219	506	100	192
MOLECULAR WEIGHT, G/MOLE	58-145	165-240	16.043	32.042	44.094	2.016
VAPOR DENSITY AT NBP, G/LITER(1)	4.4	NA	1.76	1.21	2.1	1.34
VAPOR DENSITY AT NTP, G/LITER(1,2)	4.4	NA	0.651	1.40(4)	1.81	0.084
LIQUID SPECIFIC GRAVITY AT NBP	0.70-0.78	0.87	0.425	0.796	0.593	0.071
DENSITY RATIO, LIQUID AT NBP: GAS AT NTP	166(3)	NA	650	570	340	845
DIFFUSION COEFFICIENT, FT^2-HR	0.2	0.2(4)	0.6	0.5	0.4	2.4
VAPOR VISCOSITY AT NBP, MICROPOISE	NA	NA	107	95	80	87
VAPOR VISCOSITY AT NTP, MICROPOISE	NA	NA	99	110	63	10

(1) DENSITY OF AIR AT 1 ATM AND 68°F = 1.205 G/LITER.
(2) NORMAL TEMPERATURE AND PRESSURE (NTP) IS 68°F AND 1 ATM.
(3) AT 1 ATM AND 60°F.
(4) ESTIMATED.

combustion. The presence of winds in open areas greatly affects the size of the flammable zone. In a confined space, depending upon its volume relative to the spill quantity, a pseudo-equilibrium is eventually achieved which may possibly be either too rich, too lean, or within combustible limits. The spread and dispersion of LNG vapor is currently being addressed by a number of studies associated with the Department of Energy (DOE) Liquefied Gaseous Fuels Safety Program (Refs. 7-28 through 7-31).

NG released from CNG tanks at ambient temperatures is considerably less dense than air and will tend to rise, diffuse, and disperse in unconfined spaces. Furthermore, NG vapors diffuse more readily through air than those of gasoline. These properties, in combination with the broader flammability range of NG in air, have been interpreted as indicating that a fire hazard would exist more readily with NG than with gasoline, while the fire hazard would be expected to persist longer with gasoline (Ref. 7-16). In comparison with LPG and gasoline vapors, which are heavier than air, the buoyancy and dispersion characteristics of methane vapor at ambient conditions are advantageous in unconfined areas (Refs. 7-32 and 7-33).

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7.2.2 Thermochemical Properties

Safety-related thermochemical fuel properties are listed in Table 7-6. The lower flammability limit is one criterion for evaluating relative fire hazards, especially for small leaks or spills (Ref. 7-25). This limit is roughly the same for methane and methanol, and considerably higher than for gasoline, indicating a lesser fire hazard in terms of this criterion. For closed-container storage, the wide flammability range of methanol has been identified as a cause for some concern (Ref. 7-39). In particular, vapor pressure and flammability limit data indicate that a saturated mixture of methanol vapor and air in a fuel tank is flammable at temperatures between 48°F and 106°F. Conversely, a saturated mixture of gasoline vapor and air in a closed tank is ordinarily too rich to ignite. A potential safety hazard with neat methanol is, therefore, the increased probability of fire in closed containers such as fuel tanks which have been open to the atmosphere. Methanol's wide flammability range could become a lesser concern with the use of cold startability additives, such as gasoline or pentanes, which effectively reduce the upper flammability limit (Ref. 7-39). A safety benefit of methanol and other alcohols is that, unlike gasoline, they are better conductors and thus do not produce static-generated sparks (Ref. 7-40).

Table 7-6. Thermochemical Properties of Fuels (Refs. 7-16, 7-18 through 7-20, 7-22, 7-34 through 7-38)

PROPERTY	GASOLINE	No. 2 DIESEL	METHANE	METHANOL	LPG	HYDROGEN
FLAMMABILITY LIMITS IN AIR, VOLUME PERCENT	1.4-7.6	0.7-5.0	5.0-15	6.7-36	2.4-9.6	4-75
DETONABILITY LIMITS IN AIR, VOLUME PERCENT	1.1-3.3	NA	6.3-14	NA	NA	18-59
AUTOIGNITION TEMPERATURE, °F	430-500	490	1000	725	920-1020	1060
IGNITION ENERGY, MJ	0.24	NA	0.29	NA	0.25	0.02
FLASH POINT, °F	-50	125	-306	52	-156	NA
HIGHER HEATING VALUE, BTU/LB	20,260	19,600	23,880	9,770	21,560	61,030
LOWER HEATING VALUE, BTU/LB	18,900	18,400	21,520	8,570	20,510	51,600
FLAME TEMPERATURE, °F	3,986	NA	3,410	3,570	3,595	3,710
FLAME LUMINOSITY	HIGH	HIGH	MODERATE	LOW	HIGH	LOW
QUENCHING DISTANCE AT 1 ATM, CM	0.2	NA	0.2	0.2	0.2	0.06
MAXIMUM BURNING VELOCITY, CM/SEC	33-47	33-47	39	44	35	270

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An important property of a fuel is its autoignition temperature. The autoignition temperature is the minimum temperature at which a combustible mixture of fuel and air can ignite in the absence of an external ignition source. This property is affected by a large number of factors, including the volume and material of the test apparatus, air velocity, pressure, and fuel additives (Ref. 7-41). Therefore, it cannot be considered as a fixed property of a fuel, and tabulated values are not generally valid except for the specific test conditions under which they are determined (Ref. 7-42). For example, reported autoignition temperatures for methane range from 1000°F to 1300°F, and corresponding ranges are found for a number of other gases; e.g., ethane (959-1166°F), carbon monoxide (1128-1216°F), and ethylene (914-1018°F) (Refs. 7-42 and 7-43). The autoignition temperature of NG is less than that of pure methane because of the presence of higher hydrocarbons (Ref. 7-31).

Relative to gasoline and diesel fuel, the higher autoignition temperatures of the other fuels listed in Table 7-6 would appear to reflect a lower fire hazard. However, since only small amounts of energy are needed to ignite these fuels, especially hydrogen, this is not the case. Relatively weak thermal ignition sources can ignite these fuels, e.g., sparks, matches, hot surfaces, or open flames. Even a weak spark due to the static electricity discharge from a human body may be sufficient (Ref. 7-16). Therefore, the autoignition temperature alone does not measure the relative fire hazards of fuels.

Another important safety property of liquid fuels is the flash point, the minimum temperature which generates an ignitable vapor-air mixture above the liquid surface. Liquefied methane has a flash point of -306°F and is clearly hazardous in the presence of open flames. The 52°F flash point of methanol is higher than all others, except diesel fuel, and fire danger from methanol spills should be less. Furthermore, methanol has a lower heat of combustion than gasoline, and the quantity of energy converted to radiant heat is less. At the same time, the low luminosity of methanol flames makes accidental exposure to fire a greater hazard with this fuel than with gasoline and methane. Hord reports that methane

flames, though clean burning, are yellowish in color and quite visible in daylight, while gasoline flames are similar to those of methane but are mixed with large volumes of soot and smoke so that fire detection is obvious (Ref. 7-16). Cold startability additives such as pentane, in quantities greater than 5 percent by volume, act as colorants for methanol flames (Ref. 7-39). Under the flammability hazard identification system established by the National Fire Protection Association, gasoline and methanol each are rated at 3, whereas methane and propane are assigned a rating of 4, which represents the most severe hazard (Ref. 7-44).

A number of thermochemical properties, in addition to those provided in Table 7-6, have been used by fire experts to characterize the explosive potential of fuels. Among these properties are fireball size, detonation velocity, and energy of explosion (Refs. 7-15, 7-16 and 7-45). The explosive hazards of hydrogen were determined to be considerably more severe than those of methane and gasoline due to its wide detonability limits and high burning velocity (Ref. 7-16). Hydrogen tends to undergo transition from explosive burning (deflagration), involving a subsonic flame front, to detonation, which is characterized by a supersonic flame front and high overpressures. This transition is enhanced by confined spaces.

Considerable uncertainty has surrounded the question of whether methane-air mixtures are capable of detonation, particularly under unconfined conditions (Ref. 7-46). Detonations of unconfined methane-air mixtures at ambient conditions have been observed experimentally, but only when initiated by quantities of high explosives in excess of 1 kg (Refs. 7-47 and 7-48). As pointed out by Hord, a bursting vessel is capable of generating a shock wave with the potential to initiate detonation (Ref. 7-16). It has also been observed that very small amounts of ethane, a constituent of NG, enhance the detonability of methane-air clouds (Ref. 7-46). On the other hand, unconfined LNG vapor clouds have been judged to be unlikely to detonate (Ref. 7-26).

Detonations of confined methane-air mixtures have been initiated experimentally by explosive charges weighing much less than 1 kg. A number of accidental explosions of NG in sewers and tunnels have been documented (Ref. 7-47). These accidental explosions presumably have been initiated by weak thermal ignition sources such as open flames, hot surfaces, or sparks.

7.2.3 Toxicology

Health risks assessed here are based on the relative toxicity of fuel exposure by inhalation, ingestion, or skin contact. Impacts on the physical environment relate to the consequences of accidental fuel release on terrestrial or aquatic organisms.

Table 7-7 summarizes available data on the health hazards of fuels (Ref. 7-49). Methane in sufficient quantities acts as a simple asphyxiant by displacing air, but is otherwise non-toxic. Methane is photochemically non-reactive, and it does not appear to have any adverse environmental impacts. A potential health hazard with LNG is skin tissue damage from contact with the cryogenic fluid or with cold fueling equipment. However, well established measures exist to avoid such contact. Consequently, methane fuel utilization appears to have a significantly lower adverse environmental and health impact than does the use of conventional fuels or methanol.

Table 7-7. Fuel Health Hazards (Ref. 7-49)

PHENOMENON		GASOLINE	METHANE	METHANOL	PROPANE	HYDROGEN
INHALATION	THRESHOLD LIMIT VALUE, FOR REPEATED EXPOSURE, PPM	VARIES	NONTOXIC	200	1000	NONTOXIC
	PRINCIPAL EFFECTS OF EXPOSURES ABOVE THRESHOLD LIMIT VALUE	VARIES	NONTOXIC	NARCOSIS	NARCOSIS	NONTOXIC
CONCENTRATED SHORT-TERM EXPOSURE (RELATIVE HEALTH HAZARD -- 5 IS HIGH; 1 IS LOW)	EYE CONTACT	2	-	2	-	-
	INHALATION	3	3	2	3	3
	SKIN PENETRATION	3	-	2	-	-
	SKIN IRRITATION	1	(1)	1	-	(1)
	INGESTION	2	-	1	-	-
	SUPPLEMENTAL EFFECTS	CHRONIC TOXICITY	SIMPLE ASPHYXIANT	PERMANENT INJURY	SIMPLE ASPHYXIANT	MAY ACT AS ASPHYXIANT

(1) SKIN TISSUE DAMAGED BY CONTACT WITH CRYOGENIC MATERIALS.

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Due to the relatively benign environmental and health-related effects of methane, the remainder of this subsection centers on gasoline and methanol. These fuels were addressed in a recent DOE Environmental Assessment document dealing with the use of alcohol fuels in highway vehicles (Ref. 7-40). One of the major findings of that assessment was that the public and occupational health risks associated with the use of alcohol fuels are generally equivalent to or less than the risks associated with the continued use of conventional fuels. Gasoline was considered to pose a greater risk than methanol, since it contains both proven and suspected carcinogens that can be readily absorbed by the skin or through inhalation. While acute dermal exposure to methanol can be highly toxic, the likelihood of unwitting exposure is small because, when in contact with the skin, methanol causes a burning sensation.

Methanol vapors also were considered less harmful than gasoline vapors. Furthermore, opportunities for exposure to unsafe vapor levels for either fuel were judged to be limited. Hence, vapor exposure is not a concern with neat alcohols under ambient conditions (Ref. 7-40). Unintentional ingestion of methanol does not pose a major health concern, but consumer information programs should be initiated if methanol fuel use increases significantly in the future. The effects of chronic, low-level, long-term exposure to methanol by inhalation or skin contact are uncertain. The DOE assessment pointed out that the synergistic relationships between methanol and other chemicals or drugs are also uncertain (Ref. 7-40).

The DOE Environmental Assessment concluded that potential disruption to aquatic and terrestrial environments by fuel spills and leaks will be reduced by the substitution of methanol for conventional petroleum-based fuels. This is a consequence of the water solubility and biodegradability of methanol. Rapid dilution of methanol in moving water systems minimizes the impact of aquatic spills (Ref. 7-50). Following terrestrial methanol spills, it was found that surface and subsurface soil organisms recolonize test plots relatively quickly. Some tests have shown 90 percent recovery within 3 weeks, versus 50 percent recovery in 3 to 12 months in some gasoline tests (Ref. 7-51).

7.2.4 Relative Hazards Based on Fuel Properties

A methodology for comparing the hazards of fuels based on their properties was described by Bowen (Ref. 7-15). This methodology enables a preliminary comparison of potential fuel hazards prior to consideration of hazards related to system design and installation. The hazard categories and the related fuel characteristics are summarized in Table 7-8. Table 7-9 presents the relative hazard rankings derived from the data tabulated in Tables 7-5, 7-6, and 7-7. Separate entries are provided for LNG and CNG in recognition of the differences in the properties of these two NG storage modes. The fuels are ranked within each hazard category, with lower numbers denoting less severe hazards. The hazard categories themselves are not ranked relative to one another, because the relative significance of each hazard depends on the fuel system design and application. Consequently, no overall ranking of the fuels was derived.

Table 7-8. Criteria for Fuel Hazards Comparison (Ref. 7-15)

HAZARD CATEGORY	INFLUENCING FACTORS
LEAKAGE	VISCOSITY, MOLECULAR WEIGHT, STORAGE PRESSURE
VOLATILITY	NORMAL BOILING POINT OR BOILING POINT RANGE, FLASH POINT, VAPOR PRESSURE, HEAT OF VAPORIZATION
DISSIPATION	DIFFUSIVITY, BUOYANCY OF NTP VAPOR
IGNITION	AUTOIGNITION TEMPERATURE, IGNITION ENERGY
FLAMMABILITY	FLAMMABLE RANGE
DEFLAGRATION	BURNING RATE, BURNING VELOCITY, HEAT RELEASE RATE, FLAME TEMPERATURE
THERMAL RADIATION	HEAT RELEASE RATE, FLAME EMISSIVITY
HEALTH	TOXICITY EFFECT OF INHALATION ABOVE THRESHOLD LIMIT VALUE EFFECTS OF SHORT-TERM CONCENTRATED EXPOSURE

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Table 7-9. Ranking of Relative Hazards Based on Fuel Properties (Refs. 7-15 through 7-51)

	RELATIVE HAZARD RANKING (1 IS LOW)						
		DIESEL	METHANE				LIQUID
HAZARD CATEGORY	GASOLINE	FUEL	CNG	LNG	METHANOL	LPG	HYDROGEN
LEAKAGE POTENTIAL	3	1	7	4	2	5	6
VOLATILITY	3	1	-	5	2	4	6
UNCONFINED DISSIPATION	5	6	2	2	3	4	1
CONFINED DISSIPATION	2	1	5	5	4	3	6
AUTOIGNITION	6	5	2	2	4	3	1
SPARK IGNITION	2	1	4	4	NA	3	5
FLAMMABILITY	2	1	4	4	5	3	6
DEFLAGRATION	5	6	3	4	1	2	7
THERMAL RADIATION	6	7	3	4	1	5	2
HEALTH	7	5	1	2	6	4	3

In Table 7-9, leakage potential is ranked according to fuel viscosity, molecular weight, and pressure at storage conditions. The ranking order for dissipation depends on whether the rapid dissipation of fuel vapors is considered desirable or undesirable. Rapid dissipation would be desirable in unconfined areas, since the concentration and duration of flammable fuel-air mixtures would be minimized. In confined areas, however, rapid dissipation would be undesirable since flammable fuel-air mixtures could readily accumulate. Hence, for unconfined dissipation, methane is one of the least hazardous fuels, but for confined dissipation the hazard of methane is exceeded only by that of hydrogen.

Ranking the relative ignitability of the fuels based on autoignition temperature produces results different from those based on ignition energy. For example, methane ranks second according to autoignition temperature and fourth according to spark ignition energy.

The deflagration hazard was evaluated in terms of the potential damage following the ignition of accidentally released fuel. Of the various hazard categories considered, deflagration is perhaps the most difficult to express as a fuel ranking, and there is no general agreement in the literature on this subject. The difficulty is due in part to the

large number of variables involved in estimating potential fire damage, many of which are situation dependent and vary over large ranges. An example of this variability is provided by the data of Table 7-10 on the burning rates and heat-release rates of spilled liquid pools (Refs. 7-15 and 7-16).

Table 7-10. Comparison of Burning and Heat Release Rates of Spilled Liquid Pools Reported by Two Sources (Refs. 7-15 and 7-16)

FUEL	BURNING RATE, CM/MIN		HEAT RELEASE RATE, KW/CM^2	
	REF. 7-15	REF. 7-16	REF. 7-15	REF. 7-16(1)
GASOLINE	1.0	0.2-0.9	352	70-317
DIESEL FUEL	1.4	-	560	-
METHANE (LNG)	0.74	0.3-1.2	168	68-272
METHANOL	0.14	-	24	-
PROPANE (LPG)	-	-	467(1)	-
HYDROGEN (LH_2)	2.0	3.0-6.6	187	281-617

(1) CALCULATED BASED ON THE REPORTED DATA.

Based on alternative assumptions about the relationship between fuel properties and hazards, other research may result in different hazard rankings. For example, the U.S. Coast Guard is currently developing risk analysis techniques such as the Equivalent Safety Concept, which is intended to supply a flammability or a toxicity hazard rating to cargoes on waterways under Coast Guard protection (Ref. 7-52). The cargo hazard rating is based on a combination of the physical and chemical or toxicological properties of the commodity. However, the Coast Guard has never issued a numerical ranking of hazardous cargoes (Ref. 7-53).

7.3 FUEL SYSTEM HAZARDS IN NORMAL OPERATION

This subsection examines fuel system hazards relating to potential bodily injury and property damage in normal vehicle operation. Fuel release is the principal concern in normal operation, since it can

lead to accumulation of a combustible mixture. Vehicle compartments, such as the trunk, and vehicle storage areas, such as garages, may be affected. Fuel release can occur through spills or leaks during vehicle fueling, or through malfunction of fuel system components. The normal functioning of pressure relief devices can also result in fuel release; for example, vapor venting from LNG tanks.

In the case of non-toxic methane, release of small amounts of fuel is not hazardous, provided that the gas is dispersed before its concentration reaches the lower flammability limit. The potential for leakage can sometimes be greater in gaseous fuel systems than in liquid systems, due to the higher storage pressures and lower molecular weights and viscosities. However, the actual magnitude of the hazard clearly depends on the fuel system design. The complexity of dual-fuel systems may in some cases provide a greater number of potential leakage paths than a liquid or gaseous single-fuel system. The hazards associated with NG release by leakage from fittings and by LNG boiloff appear to be controllable through the application of existing technologies and established procedures.

7.3.1 Fuel System Component Isolation

Automobiles converted to dual-fuel operation typically have trunk-mounted fuel storage system components. A widely used technique is to enclose valves, manifolds, fuel lines, and fittings within a bag or duct formed from a flexible material which is impermeable to methane. The material is cemented to the gas cylinder(s) and to the floor of the vehicle. To prevent the bag from being punctured, a protective metal screen is installed between the bag and the adjacent cargo space. The same approach can be used for vans with internally mounted fuel cylinders. Alternative isolation methods include sheet metal or foam barriers separating the trunk from the passenger compartment, and the installation of a gas-tight externally vented box around the cylinders and fittings.

7.3.2 Passenger Compartment Venting

The isolation methods just described do not prevent NG from leaking into the passenger compartment from the fuel line. The buoyancy of NG in air makes this possible. In addition, gas could conceivably leak into the passenger compartment because of a defective or damaged trunk sealing membrane in conjunction with fuel storage system malfunctions resulting from a collision, loose connection, malfunctioning valves or regulators, improper design and construction, superficial inspection, or abuse (Ref. 7-4).

Leakage of NG was simulated experimentally in the previously discussed NBS study (Ref. 7-4). In this program, methane was injected into the passenger compartment of a stationary vehicle instrumented with gas-concentration monitors. Injection rates ranged from 0.08 to 0.8 scf per minute. Some important observations are (1) vents in the roof and firewall (6 in^2 each) effectively delay explosive accumulation of methane, (2) vents promote more rapid dilution of explosive gas mixtures after leakage flow is stopped, (3) the lowest leakage flows (probably most typical of loose fittings, cracked welds, tubing splits, trunk membrane leaks, etc.) do not produce combustible gas mixtures in tests with 6 in^2 vents, and (4) the best location for an early warning combustible-gas detector is at the top center of the vehicle near the roof vent.

Floor and roof vents in the configuration recommended by NBS have some drawbacks. In addition to increased heating and air-conditioning loads, installation cost and the vent's impact on vehicle resale may concern fleet operators. Furthermore, floor vents may increase the presence of road fumes in the vehicle, and closure of the lower vent during vehicle operation may be desirable. Active venting, involving the use of fans, has also been suggested for the trunk and passenger compartments.

7.3.3 Additional Vent Requirements

Venting of the external fuel storage space is straightforward. Leakage into the engine compartment from the low-pressure line is also

possible during vehicle storage (Ref. 7-1). While the engine compartment is well ventilated when the engine is operating, gas accumulation could be hazardous at startup. Control measures include (1) an engine compartment vent, (2) vehicle storage with the hood up, (3) opening the hood prior to startup, and (4) with electrically driven cooling fans, providing brief fan operation prior to engine start.

In addition to vehicle compartment ventilation, adequate ventilation must be provided for vehicle storage locations such as garages and repair shops. In many cases, such ventilation already exists.

7.3.4 Gas-Sensing Devices

Combustible-gas detectors serve as a supplement or alternative to venting. Installation of early warning explosive-gas detectors in gaseous-fueled vehicles was strongly recommended by NBS (Ref. 7-4). For vehicle use, requirements include the following:

- Reliable operation under vibration, shock, temperature, and humidity extremes characteristic of vehicle use
- Positive indication of the presence of combustible gas by means of an audible or visual signal, or by preventing engine operation
- Readily mountable in passenger compartment
- Infrequent calibration
- Low cost

These requirements are straightforward, but stringent. In particular, many commercially available methane detectors employ a heated, catalyst-coated filament which can be poisoned by tetraethyl lead, silicones, and silicone-based compounds in the atmosphere (Ref. 7-54). Frequent calibration is needed in such cases. In addition, an inhibitor filter may be needed to prevent lead poisoning. Cost is a deterrent to the use of a detector in each vehicle, because these devices typically cost $250 or more. Less expensive devices (under $50) have been offered by Craft Home Products (Ref. 7-55). These units were originally intended

for home use and their suitability for vehicle applications has not been firmly established, although they were found to be highly satisfactory in school bus use in a small community in Colorado (Ref. 7-56). Typical current practice is to employ gas detectors at fueling facilities rather than in each vehicle.

7.3.5 Odorants

Odorants provide a simple and relatively inexpensive means of detecting gas leaks. Methane and ethane, the major constituents of NG, are virtually odorless in concentrations up to about 4 percent in air. Consequently, odorization of NG is performed by gas utilities prior to distribution, and is usually done for one or more of the following reasons (Ref. 7-57):

- Customer Protection. If customers can smell and identify gas, they can locate and stop a leak or obtain assistance. It should be recognized that odorization is only one phase of customer protection, and other practices for minimizing and locating gas leaks are usually maintained.

- Gas Leak Detection. Leaks may be detected not only on customers' premises, but also in service lines, street mains, regulators, stations, and everywhere gas is handled.

- State Regulation. More than half the states require that gas have an odor which renders it detectable at gas concentrations of one fifth the lower explosive limit and above.

A comprehensive discussion of gas odorants is presented in the Gas Engineers' Handbook (Ref. 7-57) and summarized in Volume III, Appendix C. There are some drawbacks to complete reliance on odorants for leak detection in vehicle systems. The upholstery in a vehicle tends to retain the odor even when the original source is no longer present. This situation can be overcome to some extent by means of commercial aerosol sprays and other counteragents, which neutralize the odor by either masking or modifying the odorant vapors. The potential difficulty of distinguishing

the gas odor from other ambient odors in a garage or industrial situation is another drawback.

The processes used to liquefy NG tend to remove odorants. Work is in progress by industry to identify and characterize odorants which are soluble in LNG (Ref. 7-58). However, the solubility of present day commercial odorants in LNG is insufficient for leak detection.

7.3.6 Boiloff From LNG Fuel Tanks

Venting of NG vapor from LNG fuel tanks is necessary to relieve pressure buildup caused by the unavoidable leakage of ambient heat to the cryogenic fluid. Beech Aircraft Corporation reports that its current vacuum-insulated LNG vehicle tanks provide up to 14 days storage before venting occurs (Ref. 7-59). Furthermore, the venting rate is reportedly less than 1 scf per hour, corresponding to a weight loss of about 2 percent per day. Although this boiloff rate appears relatively low, it could potentially lead to a hazardous accumulation in a garage. Consequently, LNG fleet operators have typically used open parking lots (Ref. 7-60).

A number of different controlled-combustion techniques have been proposed for dealing with the boiloff vapor. Ignition of the vented gas with automatic devices is one concept (Ref. 7-61). However, it has been reported that boiloff flow rates may be too low to support a flame (Ref. 7-62). A catalytic reactor on the vent pipe is another concept which was proposed for the Los Alamos National Laboratory (LANL) hydrogen-fueled car (Ref. 7-63). Platinum and palladium are among the most active catalysts for the oxidation of a number of fuels, including methane (Ref. 7-64). Light-off temperatures of 600°F or higher are needed for effective operation of such catalysts. This temperature could be achieved with electrical resistance heating of the catalyst substrate, similar to some commercial combustible-gas detectors (Ref. 7-54). After recent testing of an unheated catalytic reactor in a hydrogen car, the device was deemed unreliable and replaced with a small pilot flame device (Ref. 7-65).

The loss of insulating vacuum has been identified in connection with the LANL hydrogen car program as a major safety concern, because of the resulting increased boiloff rate, and the same considerations apply to vacuum-insulated LNG dewars. During a test at LANL in which the hydrogen tank vacuum was suddenly broken, all liquid hydrogen was vented in 2 hours, as opposed to the normal boiloff rate of 10 percent per day (Ref. 7-63). Boiloff rates under loss-of-vacuum conditions clearly impose a considerable load on the vapor dispersal system.

7.3.7 Component Malfunction

A CNG fuel system safety analysis performed for the DOT in conjunction with impact testing has addressed the mechanisms for fuel spillage or leakage caused by component malfunctions or normal wear and tear (Ref. 7-1). Table 7-11 lists the resultant identified component malfunctions and related safety provisions. The indicated safety provisions are not all part of typical conversion kits; hence, they may not necessarily be present in a given NG-fueled vehicle. For example, without passenger compartment vents, the hazard of fuel-line leakage remains uncontrolled. Also, driver perception of poor engine performance is not necessarily reliable.

According to the DOT safety analysis, CNG systems require periodic inspection to guarantee that no leakage occurs (Ref. 7-1). Although the user should notice gas leakage because of the odor, it is possible for a small leak to go undetected and accumulate fairly large quantities of gas in an unvented garage after several days. The report states that adequate venting has generally been provided in CNG vehicles.

7.4 FUEL SYSTEM HAZARDS UNDER ACCIDENT CONDITIONS

Fuel system hazards under accident conditions must be examined from a number of interrelated perspectives. In the following discussion, fuel system hazards are identified, and the relative hazards are compared for the following fuel systems: (1) gasoline, (2) diesel fuel, (3) CNG alone and in a dual-fuel system with gasoline, (4) LNG alone and in a dual-fuel system with gasoline, and (5) methanol.

Table 7-11. Safety-Related Component Malfunctions (Ref. 7-1)

COMPONENT	MALFUNCTION	SAFETY PROVISION
STORAGE CYLINDER	OVERPRESSURIZED	REFILL LINE BURST DISC. SET TO RUPTURE AT 3,000-3,600 PSI
MANIFOLD LINE	LEAKAGE INTO TRUNK	TRUNK VENT
HIGH-PRESSURE SOLENOID VALVE	STICKS OPEN	UNLIKELY SINCE INLET PRESSURE WILL CLOSE VALVE. HAS NO EFFECT IN NORMAL OPERATION
HIGH-PRESSURE FEED LINE	LEAKAGE	PASSENGER COMPARTMENT VENTS OR ISOLATION
HIGH-PRESSURE REGULATOR	VALVE SEAT LEAKAGE (ALLOWS HIGH PRESSURE GAS IN LOW PRESSURE LINE)	INCREASING PRESSURE TENDS TO CLOSE VALVE. REGULATOR LEAKS TO ATMOSPHERE AT 2,000 PSI OUTLET PRESSURE. LOW-PRESSURE SOLENOID WILL NOT OPEN ABOVE 600 PSI INLET PRESSURE.
LOW-PRESSURE LINE	LEAKAGE TO ENGINE COMPARTMENT	NO MAJOR PROBLEM WHEN ENGINE IS OPERATING. COULD BE HAZARDOUS AT START-UP.
LOW-PRESSURE SOLENOID	STICKS OPEN	NOT LIKELY SINCE INLET PRESSURE WILL CLOSE VALVE. CLOSE HIGH-PRESSURE SOLENOID.
LOW-PRESSURE REGULATOR	VALVE SEAT LEAKAGE (ALLOWS DISCHARGE PRESSURE BUILDUP)	DRIVER WILL NOTICE POOR ENGINE PERFORMANCE AND TURN SYSTEM OFF. REGULATOR WITHSTANDS 60 PSI OUTLET PRESSURE.
GAS-AIR MIXER AND FEED HOSE	LEAKAGE TO ENGINE COMPARTMENT	LEAK CAUSES LEAN MIXTURE AND POOR ENGINE PERFORMANCE. DRIVER WILL NOTICE.
HIGH-PRESSURE LINE TO DASH GAUGE	LEAKAGE	FOLLOWER PLUG CLOSES LINE.
MANIFOLD VACUUM SWITCH	CONTACTS STICK CLOSED WHEN ENGINE IS NOT OPERATING	NO EFFECT IF IGNITION SWITCH IS OFF.

Hazards are identified by examining the potential consequences of postulated accident scenarios. Hazard control measures, including existing and proposed technologies, are then discussed and evaluated in the context of current highway vehicle design practice and experience with conventional fuels.

One approach for comparison of fuel system hazards is to examine systems of equal energy content. This approach emphasizes the design consequences of different fuel properties. For example, CNG has a lower energy density than gasoline, and a corresponding increase in fuel storage volume would normally be necessary to provide an equivalent driving range. However, operators have thus far been willing to accept reduced vehicle range with CNG, since most vehicles also have gasoline capability.

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Furthermore, dual-fuel vehicle operators differ in the amounts of each fuel normally carried on board. Consequently, the approach selected here is to address typical in-use systems which may have widely differing energy contents.

7.4.1 Hazards Identification and Accident Scenarios

The hazards associated with highway vehicle fuel systems under accident conditions are categorized as (1) fuel release upon impact, (2) fuel tank rupture in fire, and (3) intrusion of fuel system components into the passenger compartment.

Fuel release on impact can result from tank puncture or from damage to other fuel system components. Fuel tank rupture from over-pressure due to fire can result in fuel release, explosion of the fuel tank, and damage to persons or property from the resulting shrapnel. Intrusion of fuel system components into the passenger compartment can cause physical injury to the passengers. Two failure modes can lead to fuel tank intrusion into the passenger compartment: (1) failure of the cylinder retention system as a result of impact deceleration forces, and (2) in a rear-end impact, insufficient available crush distance.

7.4.2 Relative Fuel System Hazards

A second fuel system added to the original gasoline or diesel fuel system introduces additional components which can be damaged in a collision, thereby leading to fuel release, fire, or possible explosion. Failure of a CNG cylinder retention system in a crash is one example. Damage to engine-compartment-mounted components in a frontal impact is another. Both of these failure modes were observed in crash tests of vehicles with CNG dual-fuel systems (Ref. 7-1). In addition to the fuel tanks, CNG systems have multiple pressure regulators, a mixer, solenoid valves, relief valves, and high pressure piping, all of which are subject to damage. An LNG system could receive damage to its flow control components, vaporizer, pressure regulator, solenoid valve, relief valves, and piping.

The larger total tank volume of dual-fuel systems increases tank vulnerability. Fire from release of one fuel can cause damage, fire, or explosion of the other fuel system. The release of both fuels often broadens the flammability range. A detailed portrayal of the damage phenomena that could occur as a result of the gaseous fuel release is presented in Reference 7-2. "Unlike gasoline, these fuels either are gaseous or become gaseous on release from their containers. Thus, when these fuels spill, they disperse in the air and produce potentially flammable mixtures over a large volume. These mixtures can be ignited by various ignition sources on a motor vehicle (hot manifolds, sparks, etc.) producing, in a relatively inconfined (sic) area, a high-intensity, short-duration fire ball. Other combustibles--such as clothing or the vehicle interior--may then ignite and exposed skin may suffer burns. If the gas vapors are trapped in a confined area (sewage drains or culverts), subsequent ignition would result in an explosion and extensive personal injury and property damage."

An explosion might occur without initial NG release, if the NG fuel tank is exposed to a fire. The fire could be caused by fuel spilled from another vehicle or by fuel spilled from the tank of a dual-fuel vehicle. In this case, the fire would increase the fuel tank pressure and, if the pressure relief device failed to operate, the tank would probably burst. The resultant pressure wave and explosive debris might damage nearby structures. Subsequent ignition of the released gases would further intensify the fire (Ref. 7-2).

Current CNG tanks designed to DOT standards are quite rugged compared to the conventional fuel tank or most other parts of a car or truck. Lightweight CNG tanks might be more vulnerable to collision damage and fires. Current developments in lightweight CNG tank technology are discussed in Section 2.

Double-wall, insulated LNG tanks for highway vehicle applications are typically designed to accommodate working pressures of up to 60 psi. Hence, the required inner wall thickness is considerably less than

that of CNG tanks. The double wall construction protects against puncture, and the insulation retards LNG heating in a fire. A review of the safety experience of LNG truck operators reveals several accidents in which LNG trailers have withstood rollovers, head-on collisions, and fires which have destroyed the tractors (Ref. 7-47).

Venting of LNG from an overturned vehicle is a concern. In this situation, liquid occupying the normal vapor space could be forced from the vent line under pressure. A rollover valve is used in current gasoline systems to prevent liquid from escaping through the vapor vent line, and a similar device could potentially be designed for LNG applications.

7.4.3 Control of Fuel Release Upon Impact

Fuel release during and after vehicle crashes is of obvious concern. For vehicles which use fuels with a boiling point above 32°F, which includes methanol, Federal Motor Vehicle Safety Standard 301 specifies fuel system integrity requirements (Ref. 7-66). This standard applies to passenger cars and to multipurpose passenger vehicles, trucks, and buses that have a gross vehicle weight rating (GVWR) of 10,000 lb or less and to school buses with a GVWR greater than 10,000 lb. For vehicles with a GVWR of 10,000 lb or less, fuel spillage is limited to specified amounts during and after tests which include a fixed frontal barrier crash, rear and lateral moving barrier crashes, and a static rollover test. School buses with a GVWR exceeding 10,000 lb must meet the requirements of a moving contoured barrier crash at any point and angle. All barrier crash tests are conducted at an impact speed of 30 mph, except the lateral moving barrier which impacts at 20 mph. The frontal barrier standard has been in effect since 1968, while the rear barrier crash specification is applicable to passenger cars manufactured after September 1, 1976.

The Bureau of Motor Carrier Safety of the DOT Federal Highway Administration has published regulations governing liquid fuel tanks and LPG systems. For liquid systems, construction and performance

requirements are specified, including leakage control, prevention of bursting in fire, and integrity following tank drop testing (Ref. 7-67). No corresponding integrity standards have been established for gaseous fuels.

The National Fire Codes include sections on the installation of LPG systems on vehicles, but no explicit crash test requirements are called out (Ref. 7-68). Instead, the LPG standard specifies that fuel containers shall be securely mounted to prevent jarring loose and slipping or rotating, and the fastenings shall be designed and constructed to withstand without permanent visible deformation static loading in any direction equal to four times the weight of the container filled with fuel. This 4 g static loading is considerably lower than the 50 g peak accelerations measured in some vehicle crash tests and component sled tests (Ref. 7-1).

The California Highway Patrol (CHP) has issued design and installation regulations for LPG, CNG, and LNG containers and systems used for motor vehicle propulsion (Ref. 7-69). To satisfy the CHP code, fuel containers and their cradles must be secured by means capable of withstanding in any direction a static force of eight times the weight of the fully loaded containers. Furthermore, CNG and LNG supply containers must be constructed and inspected in accordance with DOT regulations. The CHP code contains a further requirement on the crashworthiness of LNG-fueled vehicles: "Each completed container, including its supporting structure and valves, enclosures, and lines normally attached thereto, shall have structural integrity to withstand damage from deceleration and acceleration forces resulting from a 30 mph front-end and rear-end collision of the type of vehicle in which the container is installed. A test or other means shall demonstrate that the container and its openings do not rupture in such collisions." It is reported that the CHP monitors performance by inviting public comment on vehicle performance and failure by a docket complaint system. Enforcement of installation standards is loose with no periodic test programs (Ref. 7-14).

Automatic cut-off valves can control NG release in accidents. Such valves can be designed to close in any or all of the following situations: (1) no engine vacuum, (2) ignition switch off or in accessory position, (3) low engine oil pressure, and (4) broken electrical connection to valve.

Excess-flow devices have been used in CNG systems, and are required by CHP regulations for LPG containers. However, according to Dual Fuel Systems, they are not currently recommended (Ref. 7-70). In this company's experience, no design has been identified which functions satisfactorily over the wide range of pressure differentials encountered in CNG service. Improved automatic shutoff and excess-flow valves for CNG cylinders are being investigated by a technical task force of the recently formed AGA Methane Powered Vehicle System Committee (Ref. 7-71).

7.4.4 Control of Fuel Tank Rupture in Fire

Among the approaches for controlling fuel tank rupture in a fire are (1) pressure relief devices to allow controlled fuel release, and (2) sufficiently strong tanks to withstand fires. The first approach is embodied in the DOT regulations for cylinders used to transport CNG and LNG. The second approach is followed by the Italian authorities responsible for CNG vehicles. As will be apparent, the extensive experience and apparently excellent fire safety record of Italian CNG vehicles unfortunately cannot be directly extrapolated to U.S. vehicles. It must also be noted that the DOT hazardous materials regulations governing the shipment of gases do not apply to vehicle fuel systems (Ref. 7-33).

7.4.4.1 DOT Cylinder Regulations

Regulations governing the use of CNG cylinders (DOT-3AA) and LNG cylinders (DOT-4L) are contained in the Code of Federal Regulations (49 CFR 173.34), and are entitled "Qualification, Maintenance and Use of Cylinders" (Ref. 7-72). With regard to pressure relief devices, the regulation cites publications of the Compressed Gas Association (CGA), and states that: "No person may offer a cylinder charged with a compressed gas for transportation unless the cylinder is equipped with one or more

pressure relief devices sized and selected as to type, location, and quantity and tested in accordance with CGA Pamphlet S-1.1. The pressure relief device system must be capable of preventing rupture of the normally charged cylinder when subjected to a fire test conducted in accordance with CGA Pamphlet C-14." While the regulation pertaining to pressure relief devices was published only recently, it serves to codify existing practice (Ref. 7-73). The new regulation withdraws the authority to approve pressure relief devices, which was previously delegated to the Bureau of Explosives by the DOT Materials Transportation Bureau. In practice, the Bureau of Explosives had been approving such devices if they were in conformance with applicable CGA standards.

The standards of CGA Pamphlet S-1.1 require that a CNG cylinder typical of those used in vehicles be equipped with a combination rupture disk-fusible plug (Ref. 7-74). This device is intended to prevent bursting at the predetermined burst pressure, unless the temperature also is high enough to cause yielding or melting of the fusible material. The fire test referenced in the DOT regulations employs an apparatus which envelops the cylinder system in hot flue gases at approximately 1200°F (Ref. 7-75).

For LNG cylinders, CGA Pamphlet S-1.1 specifies the use of a pressure relief valve. The DOT regulations for LNG cylinders further specify that "the pressure in DOT-4L cylinders must be limited by a pressure controlling valve so sized and set as to limit the pressure to one and one-fourth times the marked service pressure. The design and installation of pressure-controlling valves must be such as to assure that they will not malfunction because of frost accumulation. The liquid portion of the gas must not completely fill the cylinder. For DOT-4L cylinders insulated by a vacuum, the pressure control valve must be set at least 15 psi lower than one and one-fourth times the marked service pressure."

Again, it is noted that while the codes of localities and states may require that vehicle cylinders must conform to DOT regulations, there are no nationally recognized codes or regulations governing these devices.

7.4.4.2 Italian CNG Vehicle Cylinders

The Italian approach to fire safety of CNG vehicle tanks is to rely on the cylinders to contain the gas. The general comments reported by the New Zealand investigating team indicate that the Italian authorities are strongly opposed to the fitting of burst disks or relief valves to cylinders installed in motor vehicles (Ref. 7-14). In their experience, such valves are an additional hazard because gas released from these devices could be the cause of ignition or could further feed the flames of an existing fire. The Italian authorities stated that the possibility of cylinder rupture due to excessive heat or mechanical damage is so remote as to remove the need for relief valves or burst disks, which have caused unnecessary problems in the past. More specifically, the Italian Ministry of Interior commented that:

- Burst disks on vehicle cylinders are not required, as they are not reliable and can leak.
- The way burst disks are incorporated into the system is critical, as it represents another weak link in the system.
- A burst disk on the fuel line is not permitted due to freezing problems.
- Burst disks on the cylinder would only be considered where the flow on bursting is not throttled by the valve stem.
- Use of a manually operated safety valve is required

According to the Italian Ministry of Transport, there are no records of any vehicle cylinder explosion. This statement is amplified by the comments of Tartarini, a manufacturer of CNG and LPG conversion kits, who indicated that, where CNG vehicles have been in accidents that have resulted in fire, there have been no problems with cylinder explosion.

This is partly due to the fact that (1) vehicle fires are normally neither long nor intensive enough to cause pressure to increase beyond cylinder failure limits (normally 8800 to 9600 psi), and (2) the fire will melt part of the conversion kit, allowing gas to vent into the engine compartment and flare there. Tartarini stated that a gas-fed fire in the engine compartment has never run back to the cylinder. They pointed out that insurance companies do not alter their premiums for vehicles converted to CNG or LPG (Ref. 7-14).

7.4.5 Control of Passenger Compartment Intrusion

7.4.5.1 Retention System Failure

The previously discussed safety impact testing provided two instances of retention system failure (Ref. 7-1). In the first forward impact test, the gas cylinders moved from the trunk into the passenger compartment. The modified rack with cylinders and necessary attachments, used when the frontal impact test was repeated, weighed 316 lb. The modification consisted of a steel channel installed immediately forward of the cylinders to restrain their forward movement.

During the sled test of an LNG tank and retention system, two bolts (1/4-inch, Class 5, rated at 3,825 lb) fastening the rear tank brackets to a transverse steel angle failed, allowing the tank to rotate forward until stopped by a section of steel angle which had been installed across the rear of the passenger compartment prior to the test. The steel angle satisfactorily prevented any intrusion of the tank into the passenger compartment. These results, along with four other sled tests in which significant cylinder movement occurred, show that retention systems which may appear to have been sturdily fabricated and securely attached can be subject to failure in vehicle impacts.

If the NG tanks can be mounted under the vehicle body, retention system design to prevent passenger compartment intrusion is easier. This approach has been employed recently by the Ford Motor Company in a prototype single-fueled LPG sedan. The vehicle uses two LPG tanks, totaling 25 gallons capacity and mounted beneath the car in place of the gasoline tank and spare tire well. Ford has also reported the

development of a single-fuel CNG Mercury Zephyr featuring five lightweight, advanced-technology CNG tanks of spun aluminum/glass fiber construction. Three tanks are mounted underneath the vehicle, replacing the gasoline tank, and the other two tanks are trunk mounted (Ref. 7-76).

7.4.5.2 Rear Impact

To reduce the danger of passenger compartment intrusion of a trunk-mounted fuel tank in a rear impact, adequate crush distance must be provided between the rear bumper and the fuel cylinders. In the single previously discussed rear impact test, it was estimated that up to a 27 mph impact could have been tolerated without jeopardizing rear seat occupants (Ref. 7-1).

These results apply only to the vehicle and fuel tank configuration tested. More contemporary designs may employ features which could increase the hazard of trunk-mounted NG cylinders in rear impacts. First, gasoline or diesel fuel tanks may be mounted between the rear wheels or under the rear seat as shown in Figure 7-1, allowing the entire rear compartment to serve as a crumple zone (Ref. 7-77). Secondly, the size of the rear compartment is decreased in downsized vehicles. Both of these features reduce the available crush distance. As in the case with retention system design for frontal impact crashworthiness, mounting of NG tanks under the car body may lessen the hazard to passengers in a rear impact situation. Although current automobiles provide no space for underbody mounting of NG tanks with dual-fuel operation, such mounting is apparently feasible for some vehicles dedicated to NG operation.

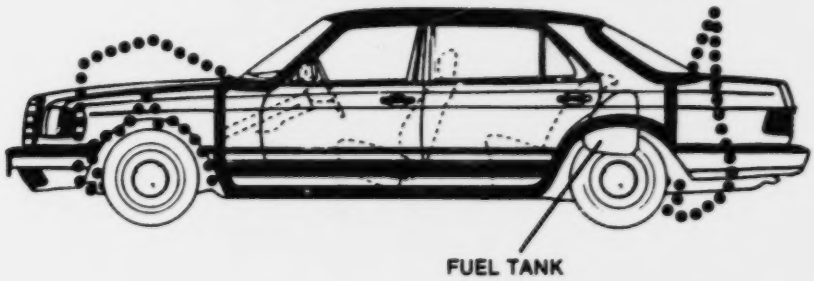

Figure 7-1. Example Car Body Design Using Collapsible Body Sections to Enhance Impact Safety (Ref. 7-77)

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SECTION 8

USER ECONOMICS

This section examines the economics of natural gas (NG) and methanol as vehicle fuels from the user viewpoint. Recent economic assessments of NG applications conducted by a number of organizations are reviewed, and an algorithm is presented that allows rapid assessment of specific NG usage scenarios.

8.1 FACTORS IMPACTING NG USER ECONOMICS

Assessment of the economic feasibility of NG as a fuel for fleet vehicles requires consideration of a number of engineering and financial factors. Important engineering parameters are (1) the heating values of NG and gasoline, (2) NG and gasoline vehicle fuel economy over the applicable driving cycle, (3) fleet fuel economy improvement as older vehicles are replaced with more fuel-efficient vehicles, (4) the fleet replacement rate, (5) the annual distance driven by vehicles in the fleet, (6) the size of the fleet, (7) the required vehicle range, and (8) the fraction of total mileage actually driven on NG following vehicle conversion.

Key financial parameters are (1) the costs and cost escalation rates of NG and gasoline, (2) the required initial capital expenditures, (3) the debt-to-equity ratio, (4) the debt interest rate and term, (5) the discount rate applied to future capital flows, and (6) tax considerations. The latter item is highly dependent on the individual user's current tax situation and local tax requirements.

8.2 RESULTS OF RECENT NG ECONOMIC ASSESSMENTS

Recent studies of vehicle compressed natural gas (CNG) user economics show a wide diversity of results, as illustrated in Table 8-1. This diversity is directly related to variations in key engineering and financial parameters, and the economic analysis methods employed (Refs.

Table 8-1. Summary of Recent CNG User Economic Studies

FLEET TYPE	PRICE, $/EQUIV. GAL. NG	PRICE, $/EQUIV. GAL. GASOLINE	PRICE ESCALATION, $/YR NG	PRICE ESCALATION, $/YR GASOLINE	INITIAL COST, $000	DEBT TO EQUITY RATIO	RETURN ON EQUITY, % BEFORE TAX	RETURN ON EQUITY, % AFTER TAX	PAYBACK PERIOD, YRS	SAVINGS, $/YR	REF.
DUAL FUEL SYSTEMS											
25 LAUNDRY VEHICLES	$0.39	$1.20	16	12	$99.7	4	-	60 (1 YR) 130 (3 YRS)	2.3[1]	-	B-1
18 FORKLIFTS	0.46	1.03	16	12	58.8	4	-	20 (1 YR) 90 (10 YRS)	3.5[1]	-	B-1
23 UTILITY VEHICLES	0.30	0.84	16	12	87.9	0	-	11 (6 YRS) 19 (10 YRS)	3.7[1]	-	B-1
FISHER-PRICE TOYS											
50 AUTOS	0.38[2]	1.00[3]	5	5	-	1	9 (5 YRS)	-	-	-	B-2
50 DELIVERY VANS	0.38[2]	1.00[3]	5	5	-	1 1	24 (10 YRS) 24 (10 YRS)	-	-	-	B-2
DOE-POSSUM											
200 VEHICLES	1.25	1.10	11	20	1500	-	-	-	1	-	B-3
400 VEHICLES	0.88	1.10	11	20	2000	-	-	-	<1	-	B-3
GLS PROJECT PLAN											
100 AUTOS	0.54[2]	1.30	9	3	263	-	-	20[4] (5 YRS)	3	-	B-4
GREELEY, COLORADO											
57 AUTOS	0.41[5]	1.00	20	50	97	-	-	-	-	$4200/ $266,400[6]	B-5, B-6

(1) FUTURE CASH FLOW NOT DISCOUNTED TO PRESENT VALUE.
(2) CONVERTED FROM $/MMBTU BASED ON ASSUMED 125,000 BTU/GAL (HHV) GASOLINE ENERGY CONTENT.
(3) EXCLUDES ROAD TAX.
(4) RETURN ON INVESTMENT, BASED ON NG PRICE ESCALATION DIMINISHING TO 7% FOR 1986-1990.
(5) CONVERTED FROM $/CCF BASED ON ASSUMED 925 BTU/SCF NG AND 125,000 BTU/GAL (HHV) GASOLINE ENERGY CONTENT.
(6) FIRST/FIFTH YEAR. NOTE PRICE ESCALATION ASSUMPTIONS.

8-1 through 8-6). The methods used in these studies range from simple payback analyses, which ignore the time-related value of money, to assessments of return on investment or equity employing various CNG and gasoline cost escalation scenarios. As indicated in Table 8-1, return on equity ranges from 9.2 percent, on a before-tax basis, to 130 percent after consideration of taxes. Payback or breakeven occurs in the first year at the earliest and, on the basis of a simplified analysis, after 3.7 years at the latest. No similar information was found in the literature for vehicular LNG systems.

Two of the most important parameters affecting economic feasibility are the price and cost escalation rates of CNG and gasoline. In Table 8-1 these parameters varied over wide ranges, reflecting expectations at the time the particular studies were performed. For example, the City of Greeley, Colorado, projected a gasoline cost escalation rate of 50 percent per year, from an initial value of $1.00 per gallon, while the American Gas Association (AGA) used 3 percent per year, from a $1.30 per

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gallon base. Projected escalation of CNG price shows less variation, ranging from 5 to 20 percent per year.

Because of the wide variations in the results of previous studies, a generalized parametric analysis was performed to determine the sensitivity of an economic figure of merit to changes in key system parameters. This was accomplished by using the discounted before-tax payback period as the figure of merit. Analysis of the long-term, after-tax, net present value of NG system investments, which would be the logical second step, was considered to be beyond the scope of this investigation.

8.3 ALGORITHM FOR ANALYSIS OF NG PAYBACK PERIOD

This subsection describes the algorithm which was used in this study to determine system payback periods, as affected by variations in the following engineering and financial parameters.

- N = number of vehicles in the fleet
- M = average total annual distance driven per fleet vehicle, miles per year
- FE = fleet average fuel economy using NG, mpg_e
- ΔP_o = initial price advantage of NG over gasoline, dollars per gallon
- a = rate of change of ΔP_o, percent $\times 10^{-2}$ per year
- i = discount rate, percent $\times 10^{-2}$ per year
- I_s = capital investment required for NG fueling station, dollars
- I_v = capital investment required for NG vehicle conversion, dollars per vehicle
- n = payback period, years

The payback period is implicitly defined by equating the present value of future fuel cost savings to the initial investment required for construction of an NG fueling station and for NG conversion of fleet vehicles. This equivalency is shown in Equation (8-1), where the variable "a" is positive for a growing NG price advantage and negative for a

declining advantage. For simplicity, yearly compounding is used for the analyses.

$$I_s + NI_v = \frac{NM\,\Delta P_o}{FE} \sum_{j=1}^{n} (1 + a)^j (1 + i)^{-j} \qquad (8\text{-}1)$$

This equation has the following closed-form solution, which defines payback period.

$$n = \frac{\log \left| 1 - \frac{FE\,(i - a)}{NM\,\Delta P_o (1 + a)} \left[I_s + NI_v \right] \right|}{\log \left[\frac{(1 + a)}{(1 + i)} \right]} \qquad (8\text{-}2)$$

8.4 CNG FUELING STATION COST MODEL

Use of Equation (8-2) requires definition of the initial capital investment for the fueling station. This parameter, which is not always available, may be expressed in terms of known fleet variables and NG compressor cost data (Ref. 8-7). Based on recent industry data, the capital investment required for a typical fueling station exclusive of installation, site-related, and other variable costs is about 150 percent of the basic compressor price (Refs. 8-5 and 8-8). Site-related and other variables include (1) the proximity of the site to suitable electrical power and distributed natural gas supplies, (2) the need for electrical transformers, (3) the number of concrete slabs required, (4) the need for fueling station walls, fencing, shelter, and driveways, (5) the amount of derating of compressor flow capacity used to account for normal wear or nonoptimal compressor operation, (6) the cost of building permits, and (7) applicable sales and property taxes.

In a recent study conducted by Dual Fuel Systems, Inc., for an 82-vehicle fleet application, the cost of concrete slabs and fences, 6 percent sales tax, and about 20 percent derating of the compressor were included in the analysis (Ref. 8-9). This resulted in a fueling station

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cost of about 250 percent of the Reference 8-7 compressor cost. The impact of this cost increase on payback period is discussed in Subsection 8.5.

Figure 8-1 presents the model of basic compressor cost versus required compressor flow capacity, Q, in standard cubic feet per minute (scfm), and Equation (8-3) relates required compressor flow capacity to previously described fleet variables. The equation is based on 7-day-per-week usage of the vehicle fleet, a compressor duty cycle of 80 percent, and a 125 scf per gallon equivalency between NG and gasoline. It does not include derating of compressor capacity to offset possible deterioration of compressor performance with time.

$$Q = 3 \times 10^{-4}\ NM/FE \qquad (8\text{-}3)$$

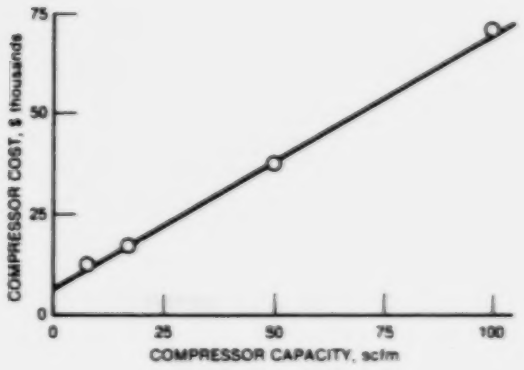

Figure 8-1. Compressor Cost versus Compressor Capacity (Ref. 8-7)

Fueling station costs in terms of required compressor flow capacity are given by Equation (8-4), which incorporates a 50 percent increase in basic compressor cost to account for associated equipment costs.

$$I_s = 10{,}500 + 933\ Q \qquad (8\text{-}4)$$

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8.5 BEFORE-TAX PAYBACK PERIOD FOR CNG

To provide a means for quickly assessing the economics of automotive CNG systems, 12 scenarios were generated and the discounted before-tax payback period was calculated for each scenario as a function of fueling station investment, compressor flow capacity, and number of fleet vehicles, while holding all other system parameters constant. Figure 8-2 presents the results for a typical scenario. As shown in the figure, the six system parameters held constant are (1) a per-vehicle conversion cost, I_v, of \$1500, (2) a per-vehicle average total annual distance driven, M, of 20,000 miles, (3) a fleet average fuel economy, FE, of 10 mpg_e, (4) an interest rate, i, of 15 percent per year, (5) a CNG price advantage relative to gasoline (including taxes), ΔP_o, of \$0.65 (1981 dollars) per equivalent gallon, (6) an increase in the NG price advantage, a, of 7 percent per year, and (7) a fueling station cost, I_s, of 150 percent of compressor cost.

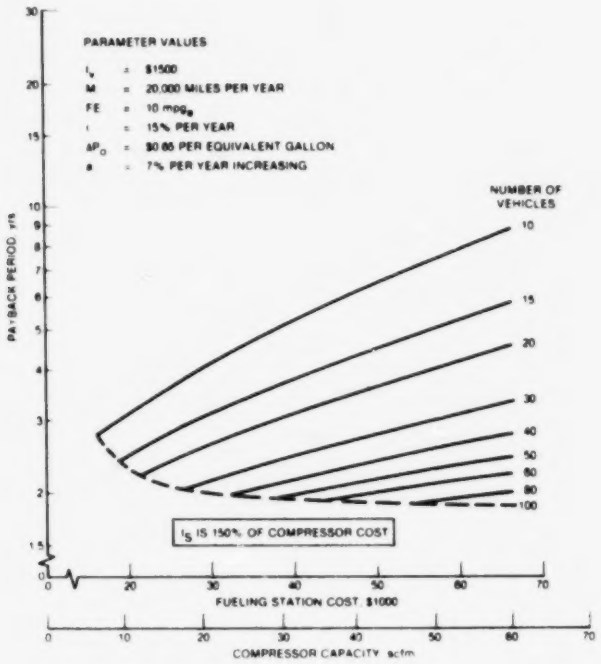

Figure 8-2. User Economics of Natural Gas as a Vehicle Fuel - Scenario 1

The dashed line in Figure 8-2 defines payback periods for optimally sized fueling stations. In this case, compressor capacity is fully utilized to accommodate fleet operation entirely on CNG. Nonoptimal payback periods occur when the fueling station is oversized, or when gasoline is used in place of CNG for a portion of the mileage accumulated by the fleet.

As shown in Figure 8-2, the optimal payback period for a 100-vehicle fleet is 1.8 years, and for a 10-vehicle fleet it is 2.7 years. However, if the optimal station for 100 vehicles serves only 50 vehicles, the payback period increases from 1.8 years to 2.5 years.

The payback period curves in Figure 8-2 can be generalized to represent other combinations of fuel economy, annual distance traveled per vehicle, and CNG price advantage. This generality is a consequence of three variables appearing as the ratio $FE/M\Delta P_o$ in Equation (8-2). For example, a fuel economy of 16 mpg, an annual distance traveled per vehicle of 32,000 miles, and a CNG price advantage of $0.65 per equivalent gallon would yield the same results as shown in Figure 8-2.

Scenario descriptions and results for 12 scenarios are presented in Tables 8-2 and 8-3, respectively. Scenarios 2 through 5 show the sensitivity of payback period to the average annual mileage traveled by individual fleet vehicles, as mileage increases from 10,000 to 60,000 miles per year. The single vehicle conversion cost is $1500, fuel economy is 10 mpg, the discount or interest rate is 10 percent per year, the initial price advantage of CNG over gasoline is $0.65 per equivalent gallon, and the rate at which the CNG price advantage increases is 7 percent per year. These four scenarios indicate that the optimal payback period for the 100-vehicle fleet declines to 0.9 year from 3.1 years as the average annual mileage traveled per vehicle increases to 60,000 from 10,000 miles. For the 10-vehicle fleet, the optimal payback period declines to 1.1 years from 4.7 years as the average annual mileage traveled by fleet vehicles increases to 60,000 from 10,000 miles. The larger percentage reduction in payback period of the smaller fleet reflects the initial benefit of distributing the fixed compressor cost over a greater number of vehicle miles.

Table 8-2. Description of Scenarios

PARAMETER	SCENARIO DESCRIPTION 1	2	3	4	5	6	7	8	9	10	11	12
I_v, $/VEHICLE	1.500	1.500	1.500	1.500	1.500	2.000	2.000	1.500	1.500	1.500	1.500	1.500
M, MI/YR/VEHICLE	20.000	10.000	20.000	40.000	60.000	10.000	20.000	20.000	20.000	20.000	20.000	20.000
FE, MPG	10	10	10	10	10	10	10	10	10	10	10	10
i, %/YR	15	10	10	10	10	10	10	20	10	10	10	15
ΔP_O, $/GAL$_E$	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.50	0.65	0.50	0.65
A, %/YR	7	7	7	7	7	7	7	7	7	0	0	7
I_S, % OF COMPRESSOR COST	150	150	150	150	150	150	150	150	150	150	150	250

Table 8-3. Discounted Before-Tax Payback Period for Optimally Sized Fueling Stations

SCENARIO	DISCOUNTED BEFORE-TAX PAYBACK PERIOD, YR, @ FLEETSIZE 10	15	20	30	40	50	60	80	100
1	2.7	2.4	2.2	2.1	2.0	1.9	1.9	1.9	1.8
2	4.7	4.1	3.8	3.5	3.3	3.3	3.2	3.1	3.1
3	2.5	2.2	2.1	1.9	1.9	1.8	1.8	1.8	1.7
4	1.5	1.3	1.3	1.2	1.1	1.1	1.1	1.1	1.1
5	1.1	1.0	1.0	0.9	0.9	0.9	0.9	0.9	0.9
6	5.6	5.0	4.7	4.4	4.2	4.1	4.1	4.0	3.9
7	2.9	2.6	2.5	2.3	2.3	2.2	2.2	2.2	2.1
8	3.0	2.6	2.4	2.2	2.1	2.1	2.0	2.0	2.0
9	3.3	2.9	2.7	2.5	2.4	2.4	2.3	2.3	2.3
10	2.9	2.5	2.3	2.2	2.1	2.0	2.0	1.9	1.9
11	3.9	3.4	3.1	2.9	2.8	2.7	2.7	2.6	2.6
12	3.8	3.2	3.0	2.6	2.5	2.5	2.4	2.3	2.3

Scenarios 6 and 7, when compared with Scenarios 2 and 3, respectively, show the effects of an increase in vehicle conversion cost to $2,000 from $1,500 per vehicle. For Scenarios 2 and 6, which compare the conversion cost effect for 10,000 annual miles per vehicle, the optimal payback period for the 100-vehicle fleet increases to 3.9 years from 3.1 years. For the 10-vehicle fleet, the optimal payback period increases to 5.6 years from 4.7 years. At an annual average vehicle mileage of 20,000 miles, the optimal payback period of the 100-vehicle fleet increases to 2.1 years from 1.7 years, while the 10-vehicle fleet shows an increase in optimal payback period to 2.9 years from 2.5 years.

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Scenarios 1 and 8 may be compared with Scenario 3 to assess the payback period increase resulting from an increase in interest rate used to discount future fuel savings to present value. For an increase in interest rate to 15 percent from 10 percent, the optimal payback period for the 100-vehicle fleet increases to 1.8 years from 1.7 years, while the optimal 10-vehicle fleet payback period increases to 2.7 years from 2.5 years. For an interest rate of 20 percent, compared with 10 percent, the payback period increases to 2.0 years from 1.7 years for the 100-vehicle fleet, and to 3.0 years from 2.5 years for the 10-vehicle fleet.

Scenario 9 compared with Scenario 3 shows the effect of decreasing the CNG initial price advantage to $0.50 per gallon from $0.65 per gallon. For the 100-vehicle fleet, the optimal payback period increases to 2.3 years from 1.7 years, and for the 10-vehicle fleet the optimal payback period increases to 3.3 years from 2.5 years.

Scenarios 10 and 11 allow assessment of the effect of a zero percent per year increase in the CNG price advantage relative to gasoline, for initial price advantages of $0.65 and $0.50 per equivalent gallon, respectively. For the 100-vehicle fleet, Scenario 11 shows a payback period of 2.6 years, compared with 1.9 years for Scenario 10. For the 10-vehicle fleet, the payback period increases to 3.9 years from 2.9 years. In a similar examination of Scenarios 11 and 9, comparing CNG price advantage increase rates of zero and 7 percent per year, respectively, optimal payback period decreases to 2.3 years from 2.6 years for the 100-vehicle fleet. The 10-vehicle fleet shows a decrease in optimal payback period to 3.3 years from 3.9 years.

Scenario 12 shows payback periods for fueling station costs equal to 250 percent of compressor cost, instead of the 150 percent factor used in all other scenarios. Compared with Scenario 1, the optimal payback period for the 100-vehicle fleet increases to 2.3 years from 1.8 years, and for the 10-vehicle fleet the payback period increases to 3.8 years from 2.7 years. These results clearly show that fueling station cost has a significant effect on payback period, especially for small fleets.

It should be noted that the data of Table 8-3 are based on 100 percent utilization of CNG. However, in typical applications, CNG utilization, which is the distance driven by a fleet on CNG divided by total distance driven, is only 75 to 80 percent (Refs. 8-6 and 8-10). As a result, the optimal payback periods shown are seldom realized. More realistic payback periods may be estimated by using Equation (8-2).

8.6 SUMMARY OF CNG USER ECONOMICS

Table 8-4 shows the sensitivity of the optimal, discounted before-tax payback period for CNG systems to changes in key economic parameters. Sensitivity is defined as the percentage change in payback period corresponding to a 1 percent change in a given parameter. The parameter group MN/FE is presented as a single entry because it represents the amount of CNG consumed per year by a vehicle fleet.

Table 8-4. Sensitivity of Discounted Before-Tax Payback Period to Economic Parameter Variations for CNG Vehicle Fleets

SCENARIO	PARAMETER	PARAMETER VALUE		OPTIMAL PAYBACK PERIOD, YEARS		AVERAGE PAYBACK PERIOD SENSITIVITY	
		WITH 10 VEHICLES	WITH 100 VEHICLES	WITH 10 VEHICLES	WITH 100 VEHICLES	WITH 10 VEHICLES	WITH 100 VEHICLES
2	MN/FE, 10^3 GAL/YR	10	100	4.71	3.07	BASE	BASE
3	↓	20	200	2.51	1.73	-0.47	-0.44
4	↓	40	400	1.46	1.08	-0.23	-0.22
5	↓	60	600	1.12	0.86	-0.15	-0.14
3	i, %/YR	10		2.51	1.73	BASE	BASE
1	↓	15		2.73	1.84	0.18	0.13
8	↓	20		2.99	1.97	0.19	0.14
10	ΔP_G, $/GAL	0.65		2.87	1.91	BASE	BASE
11	↓	0.50		3.91	2.56	-1.57	-1.47
3	A, %/YR	7		2.51	1.73	BASE	BASE
10	↓	0		2.87	1.91	-0.14	-0.10
1	I_S, % OF COMP. COST	150		2.73	1.84	BASE	BASE
12	↓	250		3.82	2.25	0.60	0.33
3	I_V, $/VEHICLE	1500		2.51	1.73	BASE	BASE
7	↓	2000		2.93	2.14	0.50	0.71

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As indicated in Table 8-4, the largest sensitivity to a parameter variation occurs for changes in the initial value of the CNG price advantage over gasoline. The 100-vehicle fleet, using an optimally sized fueling station, shows a payback period increase of about 1.5 percent for each 1 percent decrease in CNG price advantage, while the 10 vehicle fleet exhibits a 1.6 percent sensitivity. For the 100-vehicle fleet, the per-vehicle conversion cost is the second most important parameter in terms of payback period, with a sensitivity of about 0.7 percent. The fueling station investment requirement is the second most important parameter for the 10-vehicle fleet, showing a sensitivity of about 0.6 percent. Payback period sensitivity magnitudes computed for the other scenarios range from about 0.1 percent to 0.5 percent.

Based on optimally sized fueling stations, the 100-vehicle fleet shows payback periods varying from about 0.9 to 3.9 years, as individual system parameters are varied over typical ranges of values. The optimal payback period for the 10-vehicle fleet varies from about 1.1 to 4.7 years for the same parameter variations. These results indicate that the use of CNG is likely to be economically attractive for many vehicle fuel applications, especially for large fleets and when detailed after-tax assessments are conducted. However, the wide range of economic variables and uncertainties in key parameters precludes definitive general answers. Each application must be analyzed individually.

8.7 LNG USER ECONOMICS

Calculations were performed for LNG fleet conversions using the methodology discussed in Subsection 8.3. Fueling station costs used in the analysis are based on a station with a fuel storage and dispensing capability, but no provision for liquefaction. For a fleet of 100 vehicles, a fleet average fuel economy of 10 mpg on gasoline and 12.3 mpg_e on LNG, and an annual per vehicle mileage of 60,000 miles, a LNG storage tank of 1989 gallons is needed based on a 1-day tank refill period. Limited fueling station cost data, shown in Table 2-7, indicate a cost of $70,000 for a station of this capacity. The 23 percent increase in fuel economy

for LNG relative to gasoline is a result of efficiency improvements obtained from LNG related engine optimization. An LNG price advantage versus gasoline (including taxes) relative to gasoline of $0.61 (1981 dollars) per equivalent gallon was assumed in the analysis based on the purchase of commercially available LNG trucked to the fueling station and the data of Table 6-18. Vehicle conversion costs range from $1650 to $2050 per vehicle. Assumptions used for the discount rate and the increase in LNG price advantage were 10 and 7 percent per year, respectively.

Analysis of a 100-vehicle LNG fleet with an average annual per vehicle mileage of 60,000 miles and a $1650 per vehicle conversion cost yields a before-tax payback period of 0.5 year. A payback period of 3.9 years results when per vehicle mileage is decreased to 10,000 miles per year and conversion cost is raised to $2050 per vehicle. A somewhat lower payback period would be achieved if an optimally sized, lower cost fueling station were used. In general LNG payback periods are comparable to those of CNG.

8.8 METHANOL USER ECONOMICS

Methanol user economics were also examined briefly. Unlike the case with CNG, methanol can be dispensed from existing gasoline storage tanks, with some changes in fuel handling equipment materials (Ref. 8-11). Station conversion costs can be relatively small, based on experience gained in setting up two stations in California (Ref. 8-11). Therefore, the only user investment assumed to be required is vehicle conversion cost, which ranges from $1500 to $2200 for commercially available conversions, as discussed in Section 2. The current price of methanol is higher than that of gasoline on an energy-equivalent basis, even including a 20 percent engine efficiency increase assumed to result from engine modifications such as increased compression ratio. At a retail price of about $0.92 per gallon, the price of methanol corresponds to about $1.88 (1981 dollars) per energy-equivalent gasoline gallon. Therefore, it is not economically attractive for vehicle users at the present time.

Projected fuel prices detailed in Table 6-18 indicate that by 1985 methanol derived from coal may achieve a price advantage over gasoline (including taxes) of about $0.51 (1981 dollars) per energy-equivalent gasoline gallon. The discounted before-tax payback period for conversion to methanol was calculated for both extremes of vehicle conversion cost, a $0.73 (1981 dollars) per gallon effective price advantage to account for an assumed 20 percent engine efficiency increase with methanol, and an annual 1.2 percent escalation of the methanol price advantage. All other assumptions used were identical to the baseline CNG Scenario 1, except for fueling station cost which was assumed to be zero. For a vehicle conversion cost of $1500, the payback period is 1.1 years. The $2200 conversion cost yields a payback period of 1.7 years. These attractive before-tax payback periods depend strongly on achievement of the projected low cost of methanol produced from coal, and assume that the required plants could be built by that time, which is unlikely. The results do not hold for methanol produced from NG, which is more expensive than CNG or LNG on an energy basis.

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9. RESEARCH NEEDS

The assessment of issues pertinent to the use of methane-related fuels in fleet automobiles, trucks, and buses indicates that industry has made significant progress toward implementing natural gas as a vehicle fuel. However, additional research is needed in the following areas to enhance implementation of natural gas in the automotive sector. Three program categories have been identified: (1) performance, fuel economy, and emissions of natural-gas-fueled vehicles, (2) vehicle safety, and (3) studies and assessments. These needs are highlighted in the following subsections.

9.1 PERFORMANCE, FUEL ECONOMY, AND EMISSIONS OF NATURAL-GAS-FUELED VEHICLES

This research category consists of five programs, which are designed to provide the basic technical information for a confident and comprehensive assessment of the characteristics of natural-gas-fueled vehicles. The data developed in these programs are needed by system manufacturers and potential users to encourage the expanded use of natural gas in the automotive sector.

- ESTABLISHMENT OF A STEADY-STATE AND DRIVING CYCLE TEST DATA BASE, USING LATE-MODEL SPARK-IGNITION AUTOMOBILES AND TRUCKS CONVERTED TO DUAL-FUEL OPERATION.

  There is a lack of conclusive performance, fuel economy, and emissions data for vehicles tested sequentially on natural gas and gasoline. These data are needed to establish fuel economy, performance, and emissions characteristics of late-model vehicles operated on natural gas.

- DETERMINATION OF THE EFFECTS OF ENGINE RETUNING ON FUEL ECONOMY, EMISSIONS, AND PERFORMANCE OF LATE-MODEL AUTOMOBILES AND TRUCKS OPERATED WITH NATURAL GAS.

  The definition of optimal engine calibrations for natural gas in current and future vehicles requires multicylinder engine tests. Much of the existing work is based on tests

conducted with small laboratory engines, foreign designs, or older domestic engine/vehicle models. Parameters to be evaluated include spark timing, spark intensity, air-fuel ratio, exhaust gas recirculation rate, and gas induction temperature.

- ESTABLISHMENT OF DESIGN CRITERIA FOR AN OPTIMIZED SINGLE-FUEL NATURAL GAS VEHICLE.

  Coordinated research is needed to determine the performance, fuel economy, and emissions benefits of optimizing spark-ignition engines to operate solely on natural gas. Modifications such as increased compression ratio, altered valve timing, and turbocharging are expected to significantly increase engine power and reduce fuel consumption.

- INVESTIGATION OF NATURAL GAS APPLICATION TO AUTOMOTIVE DIESEL ENGINES.

  The growing usage of diesel engines in cars and trucks gives impetus to research on natural gas application to these engines. In particular, practical retrofit techniques should be investigated to allow significant near-term benefits in diesel truck fleets.

- INVESTIGATION OF UNCONVENTIONAL NATURAL GAS CONTAINMENT SYSTEMS.

  Improvement in properties of adsorptive materials, such as activated carbon, molecular sieves (zeolites), and silica gels, could result in vehicular natural gas storage systems competitive in energy density with liquefied natural gas systems. In addition, small systems for capturing natural gas vented from vehicular or fueling station liquefied natural gas tanks should be investigated.

9.2 VEHICLE SAFETY

Three research programs have been identified to resolve concerns for natural gas vehicle safety. One program involves tests of fuel system behavior under accident conditions, particularly vehicle impact and fire, and one program is concerned with cylinder corrosion. Research supporting establishment of natural gas vehicle codes and standards comprises the third program.

- EVALUATION OF NATURAL GAS SYSTEM CRASHWORTHINESS AND FIRE SAFETY.

  Limited natural gas vehicle impact tests performed more than a decade ago may not apply to current and future systems. Furthermore, no crash tests have been performed on complete vehicles with liquefied natural gas systems. Crash tests of contemporary vehicles and several state-of-the-art natural gas systems are needed to establish crashworthiness. Also needed are tests to determine compressed and liquefied natural gas tank rupture and pressure relief characteristics in crashes and fires. Compressed natural gas tests should include steel and composite cylinders with and without pressure relief devices. Liquefied natural gas tests should include several tank shapes, materials, and inner tank support designs.

- INVESTIGATION OF COMPRESSED NATURAL GAS CYLINDER CORROSION.

  Investigation of corrosion resistance of the inside of compressed natural gas cylinders exposed to natural gas contaminants is needed. Allowable contaminant levels, particularly hydrogen sulfide and moisture, should be determined for current and proposed cylinder designs and materials.

- DEFINITION OF NATURAL GAS FUEL SYSTEM STANDARDS.

  Definition of standards is needed to ensure proper design, manufacture, performance, installation, and inspection of natural gas fuel systems. No nationally recognized codes or regulations for natural gas systems exist, but the American Gas Association is currently active in this area.

9.3 STUDIES AND ASSESSMENTS

The following three programs examine potential barriers to expanded natural gas implementation in the transportation sector, and compare petroleum savings to those from alternative uses of natural gas.

- ASSESSMENT OF INSTITUTIONAL BARRIERS TO NATURAL GAS USE IN AUTOMOTIVE VEHICLES.

  Existing or potential institutional barriers to natural gas utilization in the transportation sector need to be identified in areas such as safety, emissions, and natural gas storage.

- COMPARISON OF NATURAL GAS BENEFITS IN FLEET VEHICLES VERSUS STATIONARY SYSTEMS.

  The overall resource utilization efficiency and petroleum displacement potential of natural gas in fleet vehicles should be compared to stationary applications, such as industrial engines and power plants.

- COMPARISON OF NATURAL GAS BENEFITS IN FLEET VEHICLES VERSUS CONVERSION TO ELECTRIC VEHICLES.

  The potential petroleum savings resulting from the use of natural gas in fleet vehicles should be compared to the savings available by use of electric vehicles. The fuel consumption comparison should account for the weight effects of necessary vehicle modifications.

GLOSSARY

AALA	American Automotive Leasing Association
ACL	Alcohol Conversions, Ltd.
ADL	Arthur D. Little, Inc.
AFSI	Advanced Fuel Systems, Inc.
AGA	American Gas Association
AIT	autoignition temperature
ANGTS	Alaskan Natural Gas Transportation System
AT	Autotronic Controls Corporation
atm	atmosphere
BAC	Beech Aircraft Corporation
BCF	billion cubic feet
BETC	Bartlesville Energy Technology Center
BOD	biochemical oxygen demand
BPD	barrels per day
BTC	before top center
BTDC	before top dead center
Btu	British thermal unit
CARB	California Air Resources Board
ccf	hundreds of cubic feet
CDI	capacitive discharge ignition
CFR	Cooperative Fuel Research (Council); also Code of Federal Regulations
CGA	Compressed Gas Association
CH_4	methane
CHP	California Highway Patrol
CI	compression ignition
CID	cubic inch displacement
CNG	compressed natural gas
CNGS	CNG Services, Inc.
CO	carbon monoxide
CO_2	carbon dioxide
CR	compression ratio

CRG	Catalytic Rich Gas (process)
cscf	hundreds of standard cubic feet
DCF	discounted cash flow
deg	degree (angular)
DEI	Dual Energy, Inc.
DFSI	Dual Fuel Systems, Inc.
DFVLR	German Air and Space Research Institute
DOE	Department of Energy
DOT	Department of Transportation
DRI	Data Resources, Inc.
ECE	Economic Commission for Europe
ECMI	Essex Cryogenics of Missouri, Inc.
EGR	exhaust gas recirculation
EPA	Environmental Protection Agency
FHWA	Federal Highway Administration
f.o.b.	free on board
g	gram (mass) or gravity (acceleration)
gal	gallon
gal_e	energy-equivalent gasoline or diesel fuel gallon
GC	Gibson Cryogenics, Inc.
G&E	gas and electric
GPY	gallons per year
gr	grains
GRI	Gas Research Institute
GSA	General Services Administration
GSEC	Gas Service Energy Corporation
GVW	gross vehicle weight
GVWR	gross vehicle weight rating
H_2	hydrogen
H_2O	water
H_2S	hydrogen sulfide
HC	hydrocarbon
He	helium

HHV	higher heating value
hr	hour
IACP	International Association of Chiefs of Police
ICI	Imperial Chemical Industries
IDI	indirect injection
IGT	Institute of Gas Technology
ihp	indicated horsepower
ITA	International Taxicab Association
KEP	Kaiser Electro Precision, Inc.
km	kilometer
K-T	Koppers-Totzek
L	liter
LANL	Los Alamos National Laboratory
LBT	leanest (air-fuel ratio) for best torque
LH_2	liquid hydrogen
LHV	lower heating value
LNG	liquefied natural gas
LNGS	LNG Services, Inc.
LPG	liquefied petroleum gas
LVW	linked vertical well
MAN	Maschinenfabrik Augsburg-Nurnberg A.G.
MBT	minimum (spark advance) for best torque
MHF	massive hydraulic fracturing
MJ	megajoule
MRG	Methane Rich Gas (process)
MSW	municipal solid waste
MTBE	methyl tertiary butyl ether
MVMA	Motor Vehicle Manufacturers Association
m^3	cubic meter
Mcf	thousand cubic feet
mg/ℓ	milligram per liter
mi	mile
mmBtu	million Btu

mmcf	million cubic feet
mmscf	million standard cubic feet
mpg	miles per gallon
mpg_e	miles per gallon, gasoline or diesel fuel equivalent
N_2	nitrogen
NAFA	National Association of Fleet Administrators
NBS	National Bureau of Standards
NDIR	nondispersive infrared
NFPA	National Fire Protection Association
NG	natural gas
NGL	natural gas liquids
NGPA	National Gas Policy Act
NO_x	oxides of nitrogen
O_2	oxygen
OCS	outer continental shelf
OEM	original equipment manufacturer
PDU	process development unit
PG&E	Pacific Gas and Electric
ppm	parts per million
psi	pounds per square inch
psia	pounds per square inch, absolute
psig	pounds per square inch, gage
quad	quadrillion BTU
R&D	research and development
ROI	return on investment
RON	research octane number
rpm	revolutions per minute
S	sulfur
scf	standard cubic feet
scfm	standard cubic feet per minute
SCGC	Southern California Gas Company
SDB	steeply dipping bed
SI	spark ignition

SNG	synthetic (or substitute) natural gas
SwRI	Southwest Research Institute
TCF	trillion cubic feet
UBF	unburned fuel
UCG	underground coal gasification
U.S.	United States
USGS	United States Geological Survey
VMT	vehicle miles traveled
WOT	wide open throttle

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